Wir schaffen Wissen – heute für morgen

Future linear colliders

Terry Garvey - Paul Scherrer Institut

Strategy Workshop on High Energy Particle Physics in Switzerland, Aegerisee, 9th June 2016

Linear Collider options ~ 20 years ago (a little nostalgia…)

● Next Linear Collider (NLC)	SLAC	11.4 GHz	
● Japanese Linear Collider (JLC)	KEK	11.4 GHz	
●		5.7 GHz	
● VLEPP	BINP	14 GHz	
● CERN Linear Collider (CLIC)	CERN	30 GHz	***Two beam accelerator***
(later **C**ompact **LI**near **C**ollider)		→ 12 GHz (2006)	
● SBLC	DESY/THD	3 GHz	(old technology ?)
● TESLA (DESY + int. collaboration)	DESY	1.3 GHz	***superconducting RF***

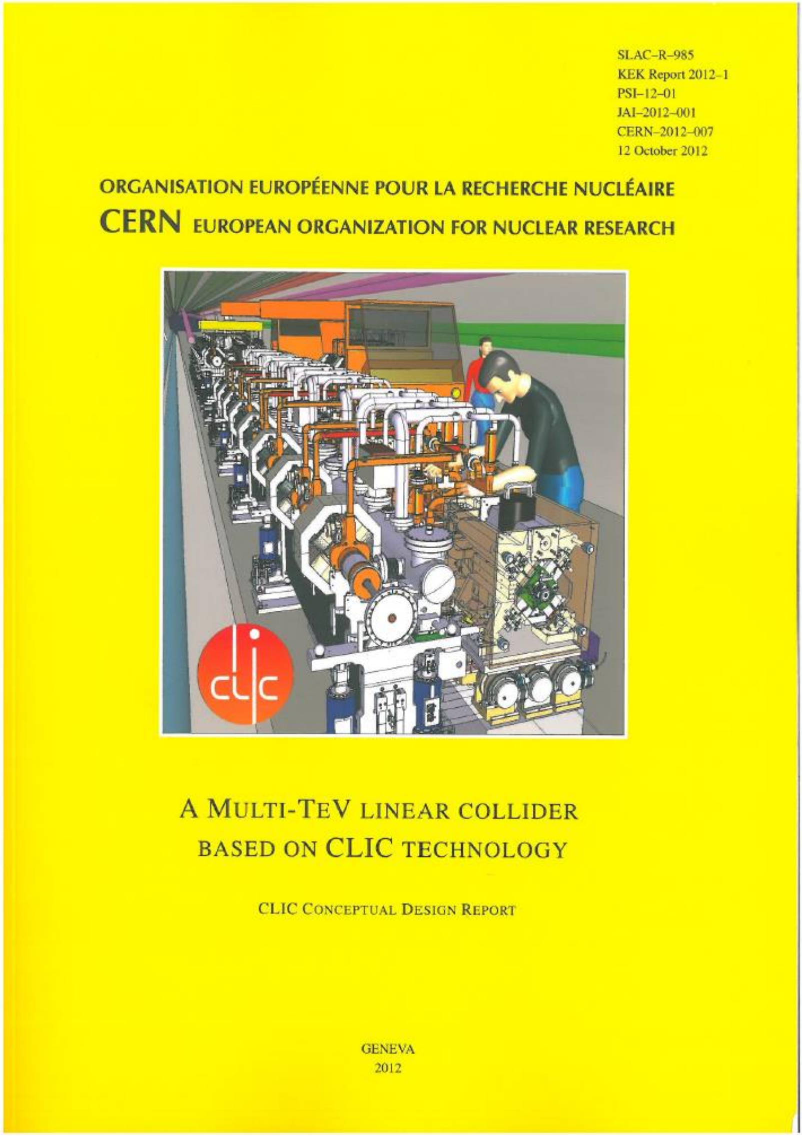
→ technology of choice for the ILC

At the time when the *International Technology Review Panel* was asked to make a recommendation the choice was between «warm» NLC/JLC and «cold» TESLA.

CERN had been 'spared' the competition as CLIC at 30 GHz was felt to be not suffciently mature for consideration.

The **cold** option was recommended (and 18 months later CERN would change to 12 GHz !)

The situation today



SLAC–R–985
KEK Report 2012–1
PSI–12–01
JAI–2012–001
CERN–2012–007
12 October 2012

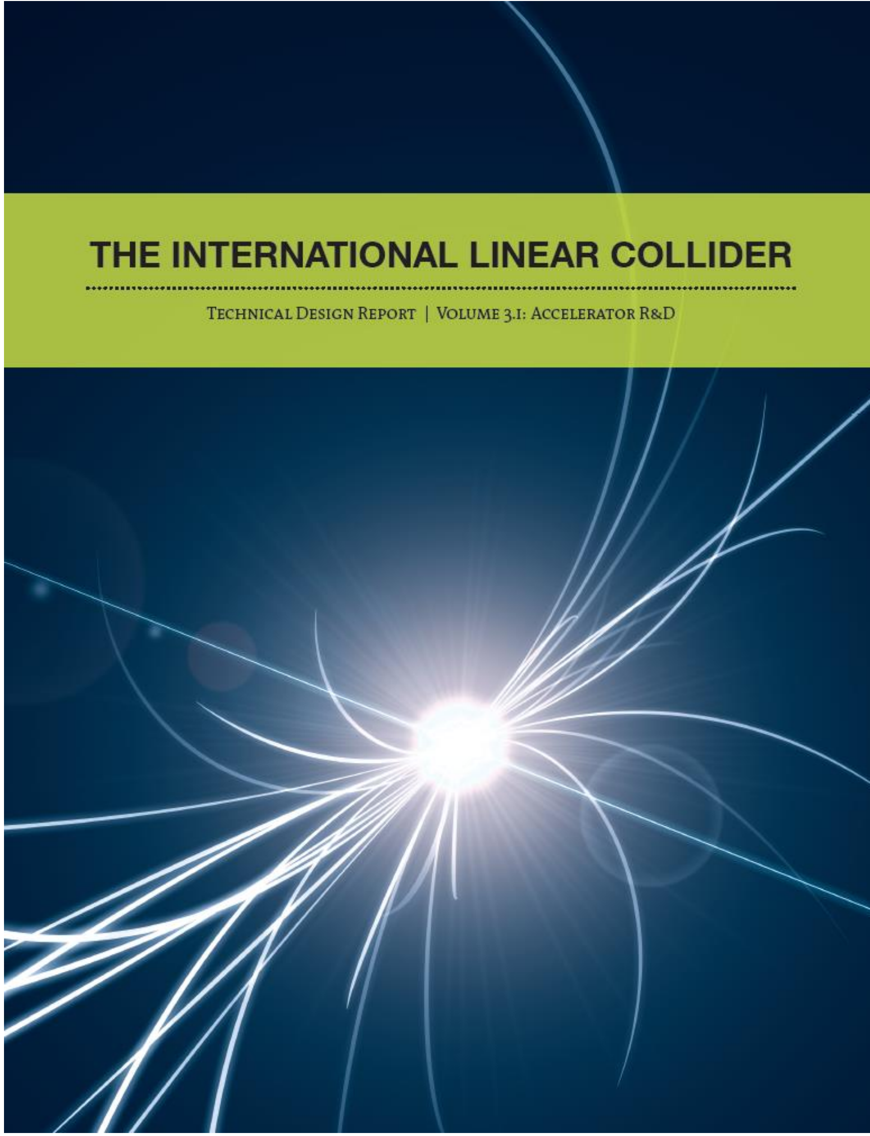
ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE
CERN EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

A MULTI-TEV LINEAR COLLIDER
BASED ON CLIC TECHNOLOGY

CLIC CONCEPTUAL DESIGN REPORT

GENEVA
2012

CDR 2012 – studied since 1985



THE INTERNATIONAL LINEAR COLLIDER

TECHNICAL DESIGN REPORT | VOLUME 3.1: ACCELERATOR R&D

TDR 2013 – studied since 1992

Beam dynamics challenges

Obtaining the required luminosity (at an affordable cost in power)

$$\mathcal{L} = H_D \frac{N^2}{4\pi\sigma_x\sigma_y} n_b f_r \qquad \mathcal{L} \propto H_D \; \frac{N}{\sigma_x} \; N n_b f_r \; \frac{1}{\sigma_y}$$

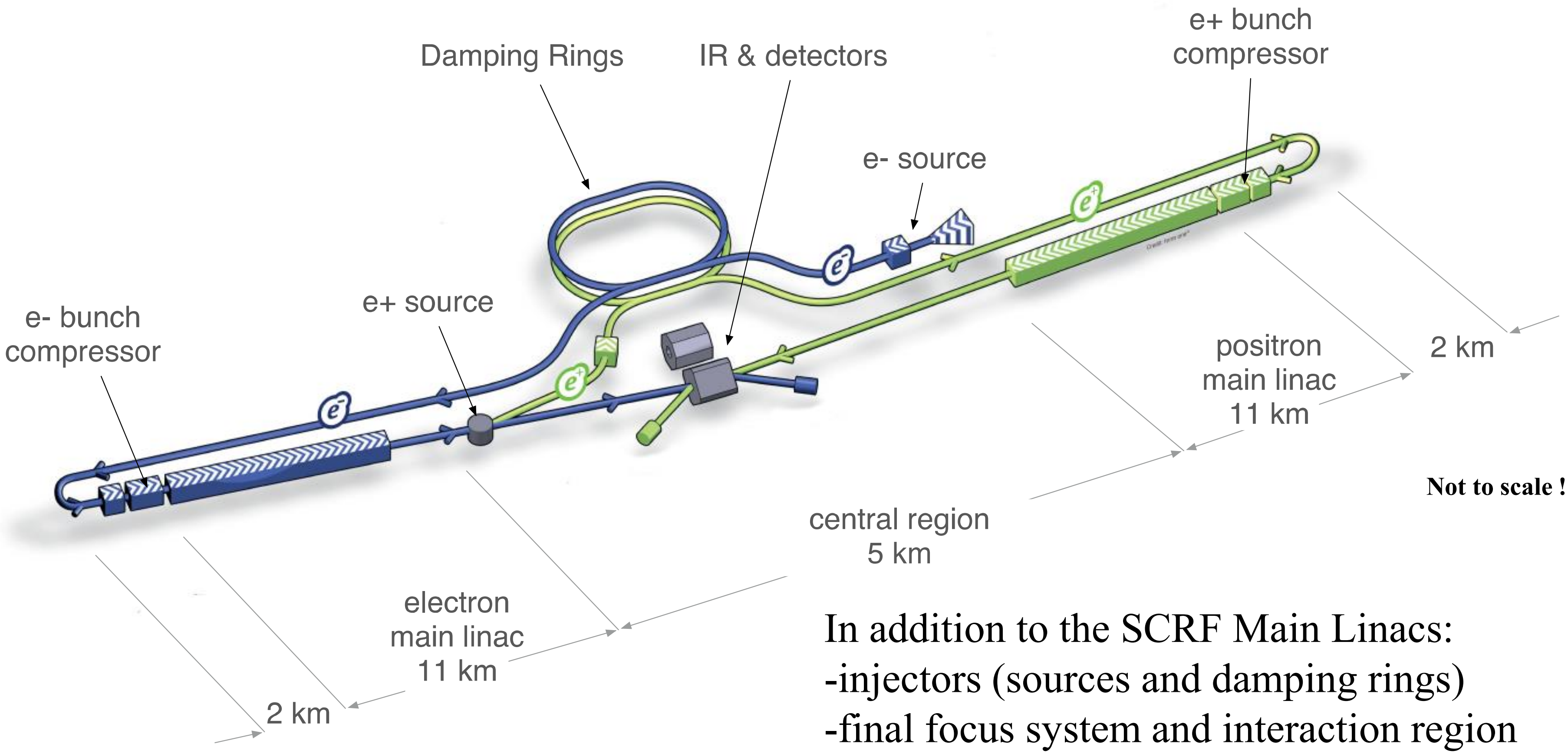
Three variables to play with; number of particles/bunch, beam power, final focus spot size.

N limited by wake-fields the bunch generates and by Disruption ($< 10^{11}$)
Transverse wakes ~ ω^3, longitudinal wakes ~ ω^2. → high N favours low frequencies.
This is the ILC approach.

Final focus spot size is restricted by need to generate beams of very small emittance and preserve this emittance during transport and acceleration through the entire linac thus imposing remarkably tight tolerance challenges on the alignment and stability of the optics and accelerating structures

However, higher accelerating frequencies allow higher accelerating gradients, in warm structures,thus reducing the length to reach a given energy.
The strong wakes limit the beam power thus necessitating smaller final focus spot sizes.
This is the CLIC approach.

Schematic of the ILC



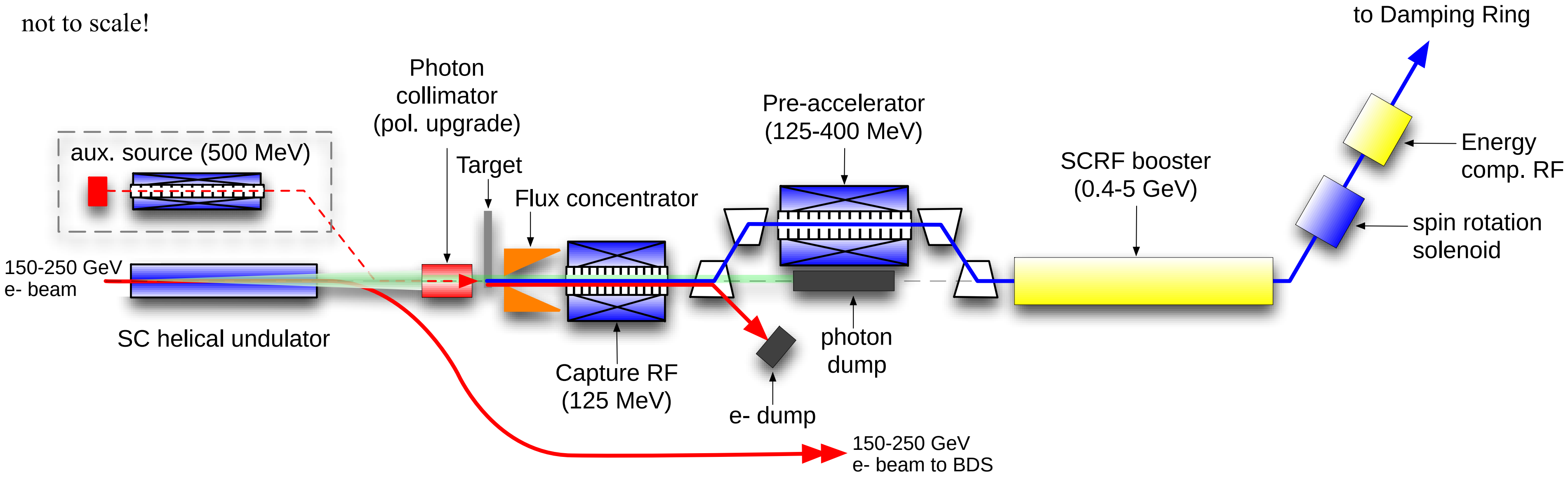
Not to scale !

In addition to the SCRF Main Linacs:
-injectors (sources and damping rings)
-final focus system and interaction region

Technology challenges – all of the above!

N. Walker (DESY)

ILC Positron Source (central region)



located at exit of electron Main Linac

147m SC helical undulator

driven by primary electron beam (150-250 GeV)

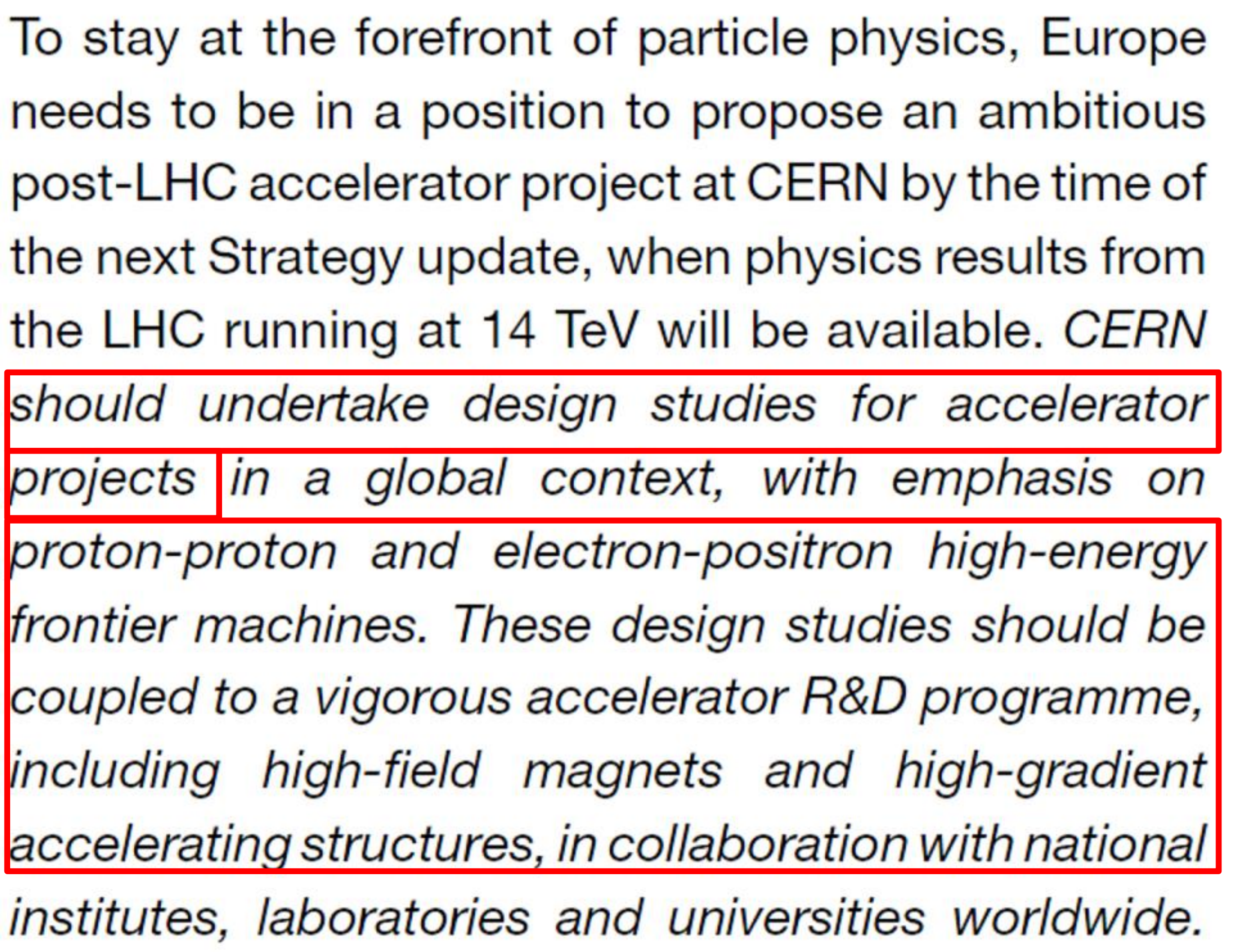
produces ~30 MeV photons

converted in thin target into e+e- pairs

There is no precedent for this – one would have to build it to verify that it works.

Challenges- high gradient cavities: quote from Strategy update 2013

Will discuss these for three reasons : (a) they were an important element in the ITRP choice of technology for ILC, (b) they were specifically mentioned in the last strategy update,
(c) *it is a subject in which PSI /EPFL has been participating.*



> To stay at the forefront of particle physics, Europe needs to be in a position to propose an ambitious post-LHC accelerator project at CERN by the time of the next Strategy update, when physics results from the LHC running at 14 TeV will be available. *CERN should undertake design studies for accelerator projects in a global context, with emphasis on proton-proton and electron-positron high-energy frontier machines. These design studies should be coupled to a vigorous accelerator R&D programme, including high-field magnets and high-gradient accelerating structures, in collaboration with national institutes, laboratories and universities worldwide.*

1.3 GHz Superconducting RF Cavity

solid niobium standing wave

9 cell cavities

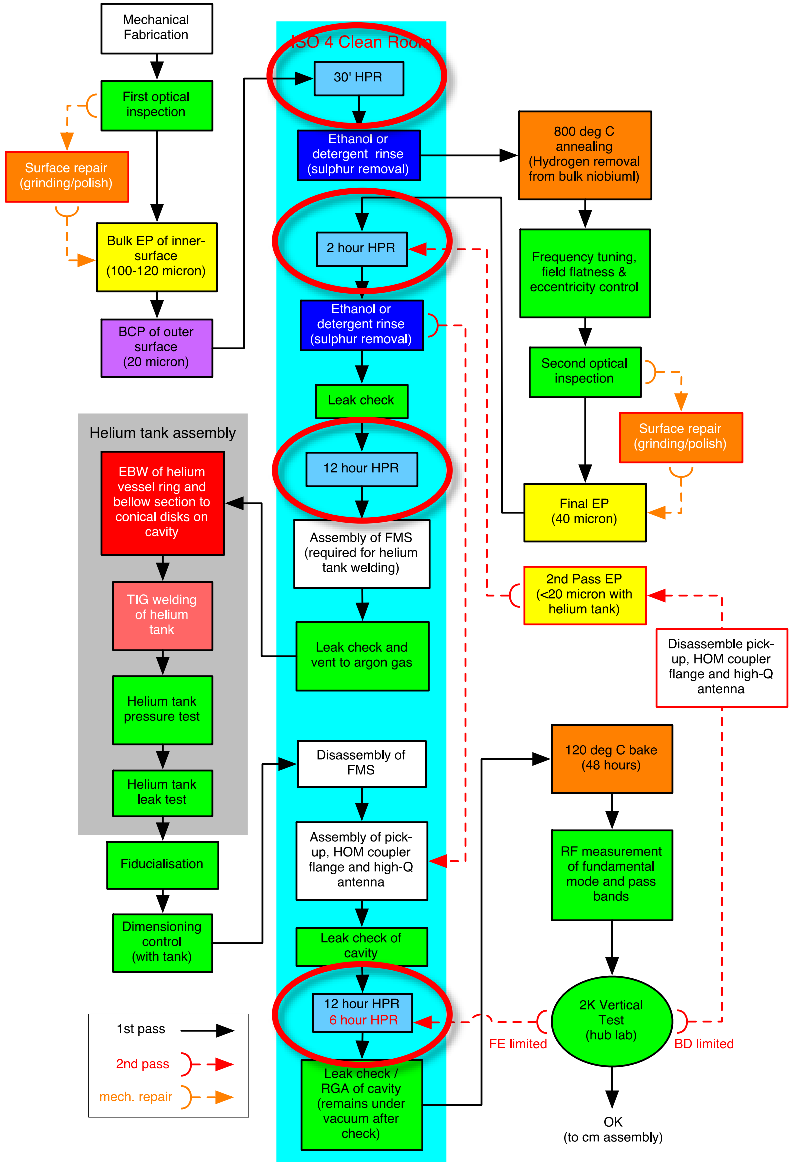
operated at 2K (LHe)

$Q_0 \geq 10^{10}$

The existence of this cavity was a major benefit to the cold option for the technology choice, in contrast to the warm X-band structures which were plagued by electrical breakdown.

N. Walker (DESY)

Road to High Performance – extensive preparation procedure the key to succes.



Mechanical Fabrication

First optical inspection

Surface repair (grinding/polish)

Bulk EP of inner-surface (100-120 micron)

BCP of outer surface (20 micron)

Helium tank assembly

EBW of helium vessel ring and bellow section to conical disks on cavity

TIG welding of helium tank

Helium tank pressure test

Helium tank leak test

Fiducialisation

Dimensioning control (with tank)

ISO 4 Clean Room

30' HPR

Ethanol or detergent rinse (sulphur removal)

2 hour HPR

Ethanol or detergent rinse (sulphur removal)

Leak check

12 hour HPR

Assembly of FMS (required for helium tank welding)

Leak check and vent to argon gas

Disassembly of FMS

Assembly of pick-up, HOM coupler flange and high-Q antenna

Leak check of cavity

12 hour HPR
6 hour HPR

Leak check / RGA of cavity (remains under vacuum after check)

800 deg C annealing (Hydrogen removal from bulk niobiuml)

Frequency tuning, field flatness & eccentricity control

Second optical inspection

Surface repair (grinding/polish)

Final EP (40 micron)

2nd Pass EP (<20 micron with helium tank)

Disassemble pick-up, HOM coupler flange and high-Q antenna

120 deg C bake (48 hours)

RF measurement of fundamental mode and pass bands

2K Vertical Test (hub lab)

FE limited

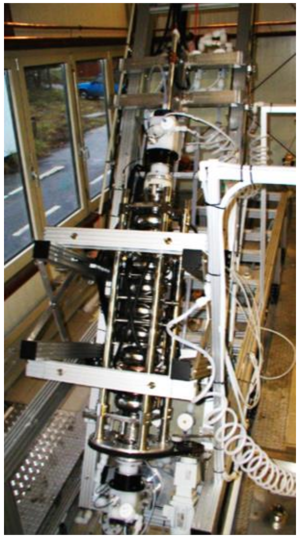
BD limited

OK (to cm assembly)

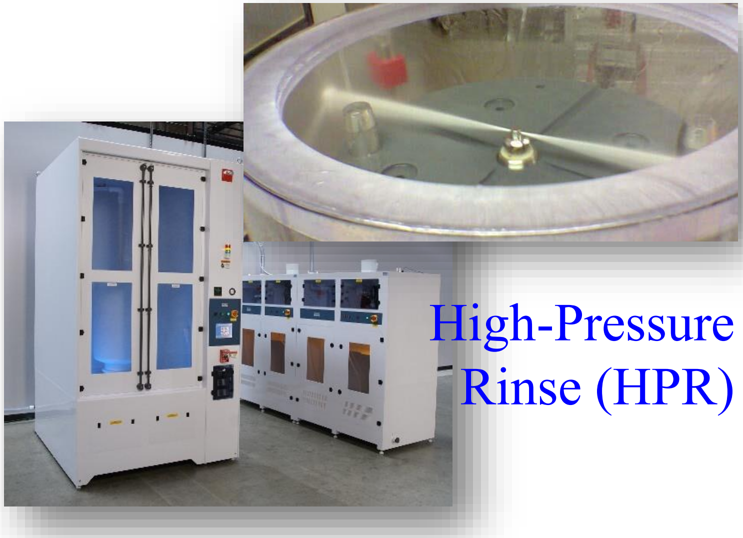
1st pass

2nd pass

mech. repair



Electropolishing

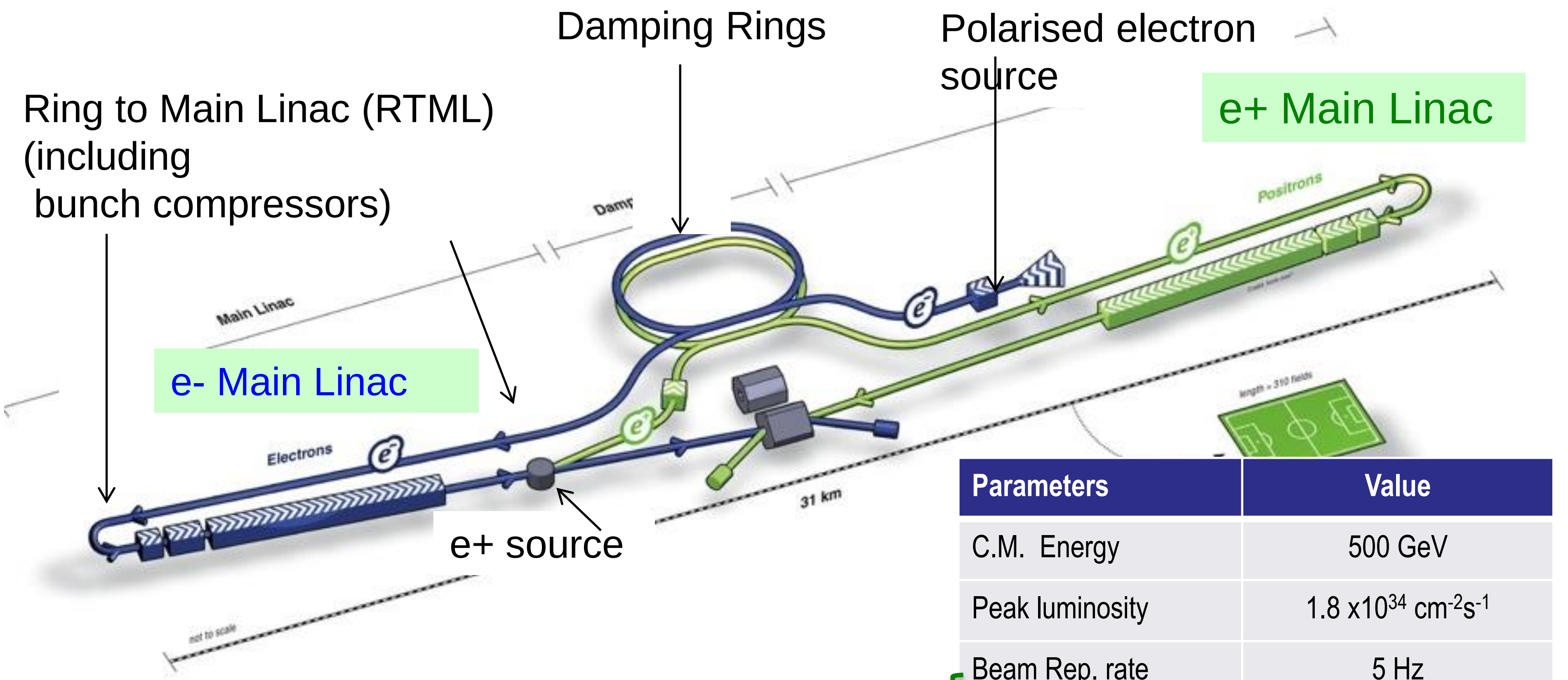


High-Pressure Rinse (HPR)

800° C annealing and
120° C baking

N. Walker (DESY)

ILC Accelerator – results since TDR



Damping Rings

Polarised electron source

e+ Main Linac

Ring to Main Linac (RTML) (including bunch compressors)

e- Main Linac

e+ source

ILC Scheme | © www.form-one.de

Parameters	Value
C.M. Energy	500 GeV
Peak luminosity	1.8 x10^{34} $cm^{-2}s^{-1}$
Beam Rep. rate	5 Hz
Pulse duration	0.73 ms
Average current	5.8 mA (in pulse)
FF beam size (y)	5.9 nm (scaled to ILC)
E gradient in SCRF acc. cavity	31.5 MV/m +/-20% Q_0 = 1E10

Demonstrated in TDR

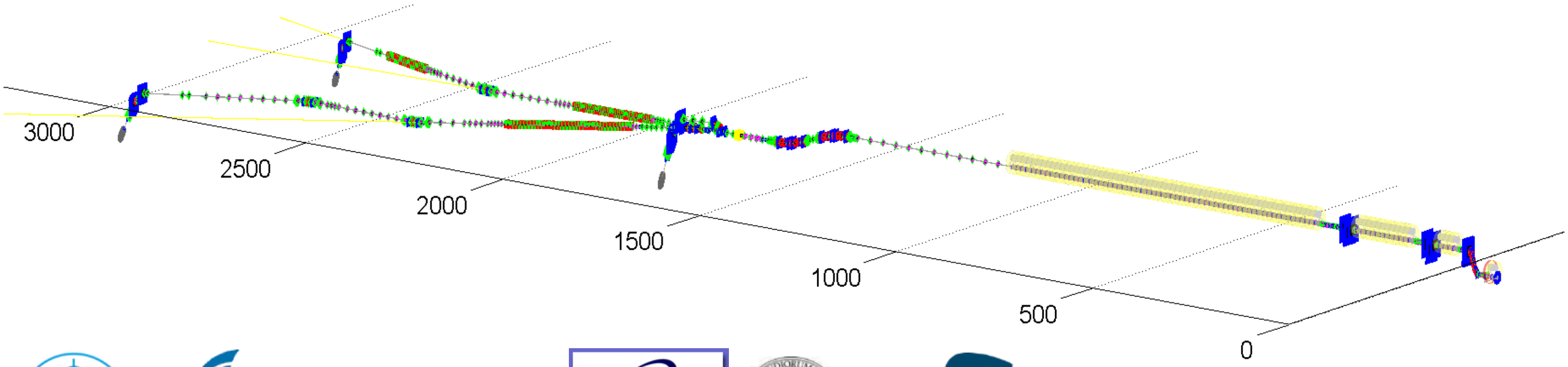
Progress in 2014-2015

European X-FEL (Accelerator Consortium)

17.5 GeV superconducting linac. 800 cavities. ***In many ways an ILC prototype !!***

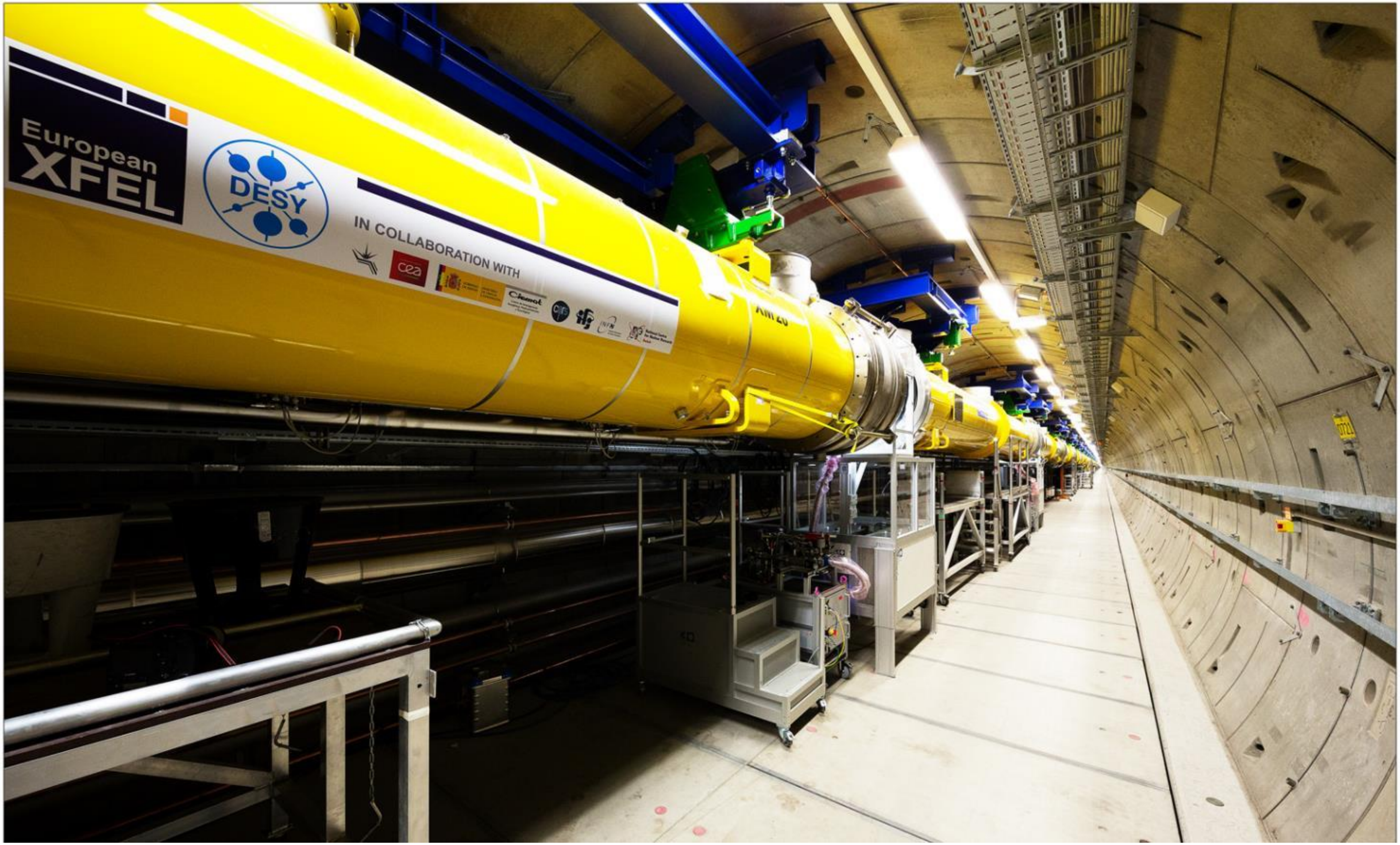
Swiss in-kind contribution
via PSI

TESLA RF technology



DESY
HELMHOLTZ ASSOCIATION
INFN Istituto Nazionale di Fisica Nucleare
irfu cea saclay
cnrs In2p3
MINISTERIO DE EDUCACIÓN Y CIENCIA
Ciemat Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas
Wrocław University of Technology
ИФВЭ IHEP
UPPSALA UNIVERSITET
Stockholm University
PAUL SCHERRER INSTITUT PSI

European X-FEL currently being installed



The CLIC structure and Characteristics of CLIC

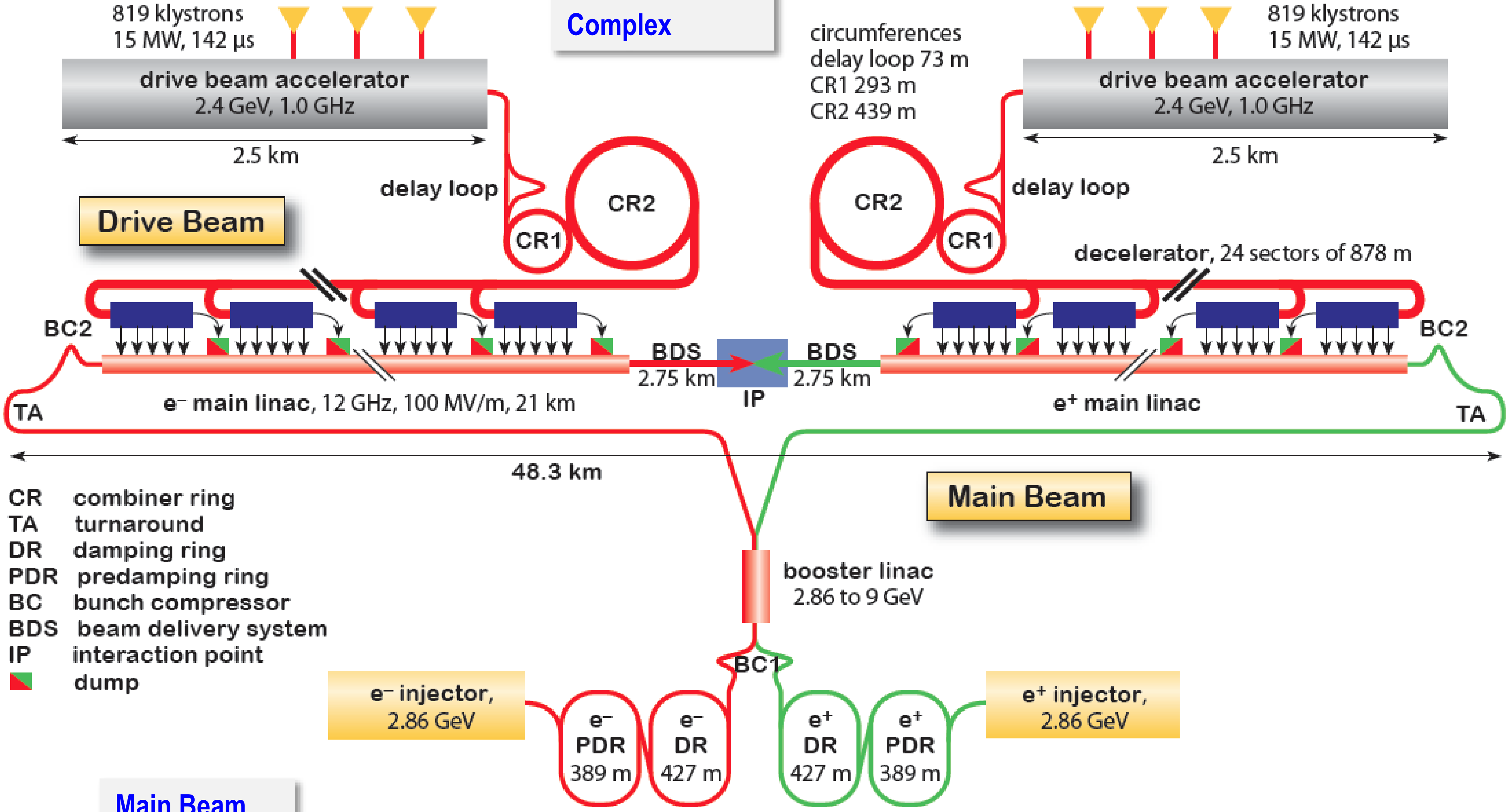
Obtain the required energy using normal conducting, high accelerating gradient, **100 MV/m**, structures with pulse lengths of the order of 200 ns.

Meet the necessary **high peak power** requirements by employing high frequency (**X-band, 12 GHz**) Structures powered by the so-called drive beam scheme (i.e. no klystrons). Structure peak input powers are ~ 250MW/m.

Meet the luminosity needs with acceptable ***high average power*** consumption by producing, transporting and colliding **low-emittance, multi-bunch** beam trains. This requires high performance damping rings, micron-level precision and alignment of the main linacs, higher-order-mode free accelerating structures, nano-meter quadrupole stabilisation and sub-nm final focus stabilisation.

CLIC Layout at 3 TeV

Drive Beam Generation Complex



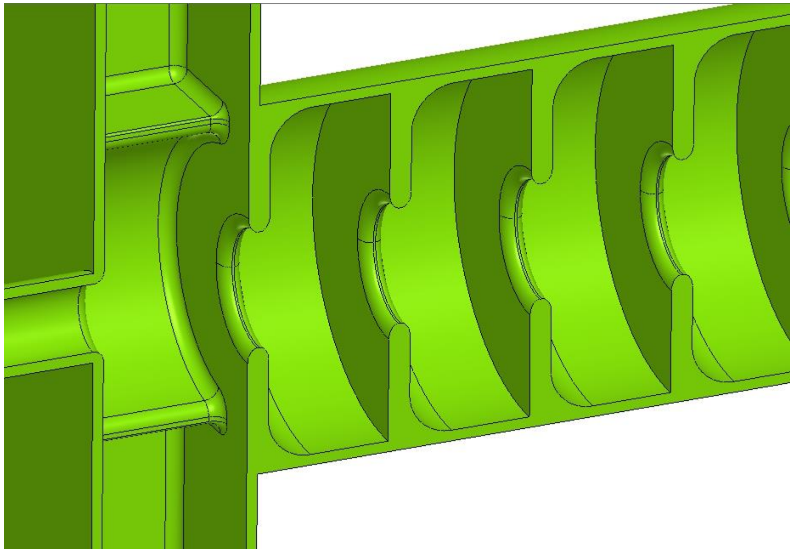
CR	combiner ring
TA	turnaround
DR	damping ring
PDR	predamping ring
BC	bunch compressor
BDS	beam delivery system
IP	interaction point
🟥	dump

Main Beam Generation Complex

What are the requirements of the accelerating structures?

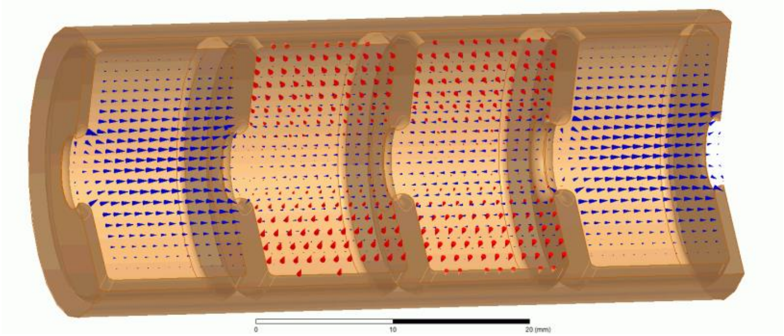
- Should reach 100 MV/m under beam loading conditions
  - keep the facility to a ‘reasonable’ length (~ 30 km of active acceleration).
- Should have higher-order-mode Q’s below ~ 10
  - reduced wake-field effects →use HOM ‘dampers’
- Should exhibit a breakdown rate (BDR) < 3x10^{-7} per pulse per meter
  - requirement to limit luminosity loss < 1%

$$BDR \propto E^{30}\tau^{5}$$



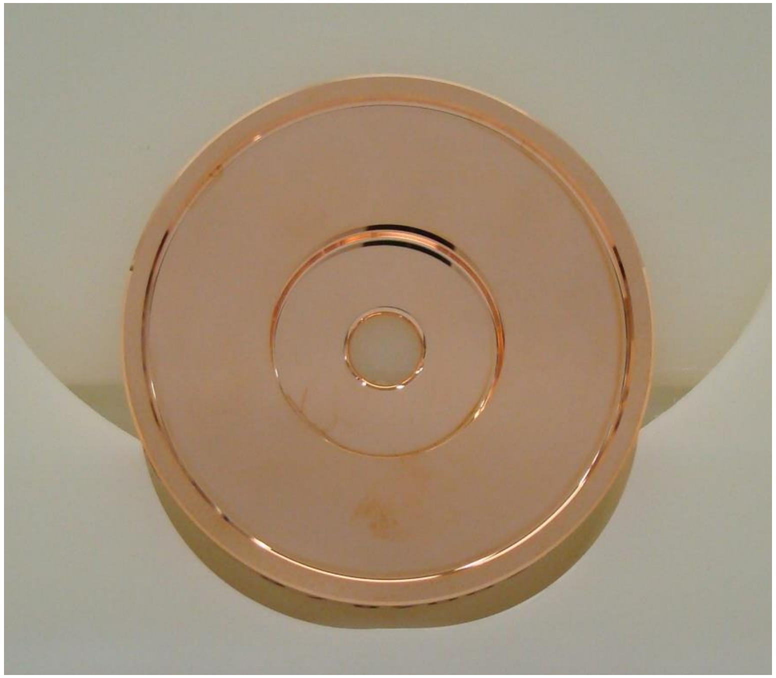
Typical multi-cell Traveling Wave structure

The structures consist of an array of resonant volumes within which the accelerating field is established.

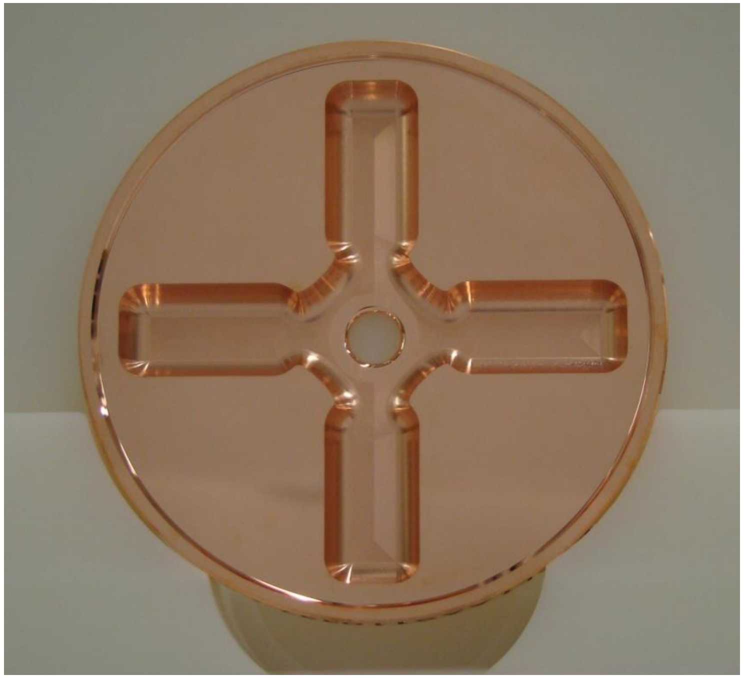


Damped and un-damped disk geometries.

Damping is achieved by coupling the higher-order-modes out into wave-guide runs perpendicular to the beam axis. The modes are then dissipated in "lossy" ceramics inserted into the WG.
The acceleration mode is "cut-off" by suitable choice of the WG width.



Un-damped

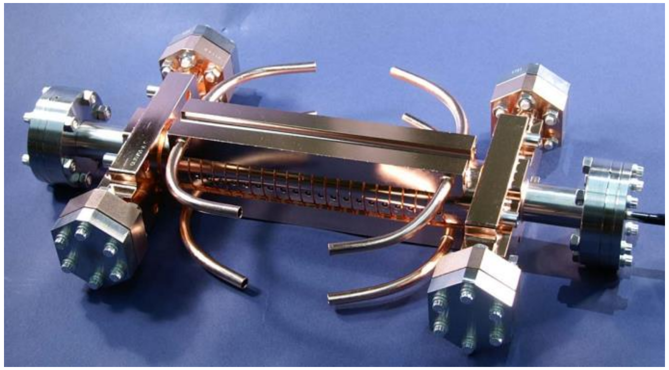


Damped

Machining is much more complicated.

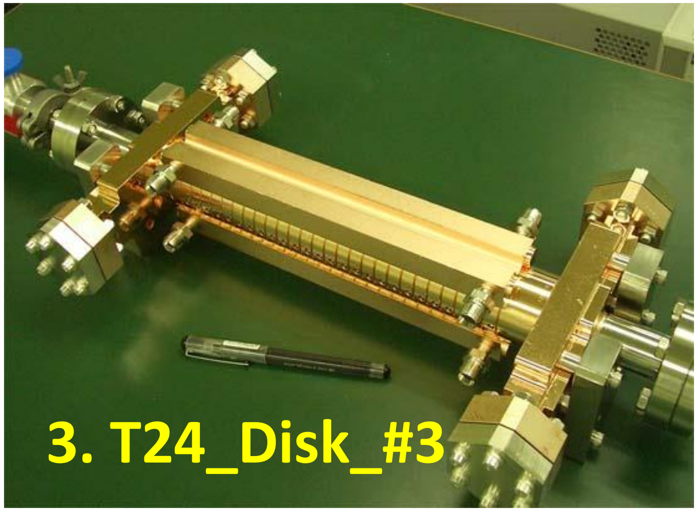
CLIC structures: Some examples: Fabrication and test

T18 →TD18→T24→TD24→TD24R05

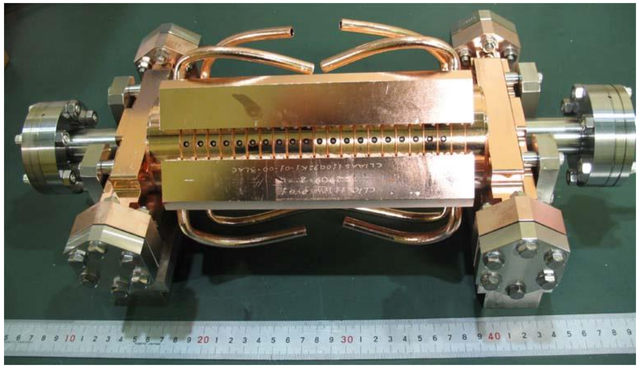


1. T18_Disk_#2

Un-damped

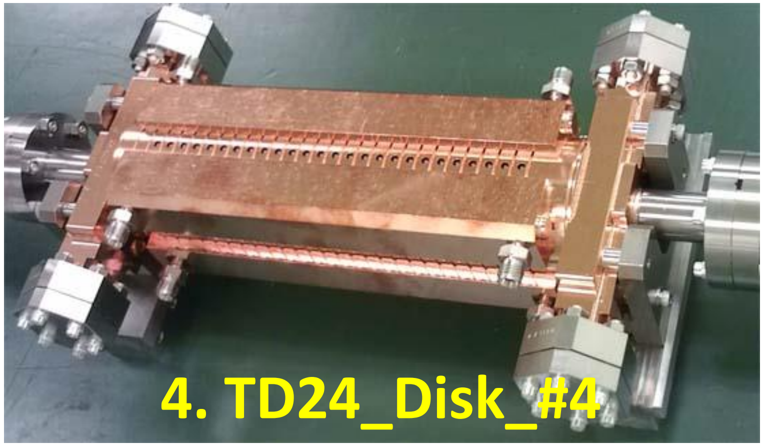


3. T24_Disk_#3



2. TD18_Disk_#2

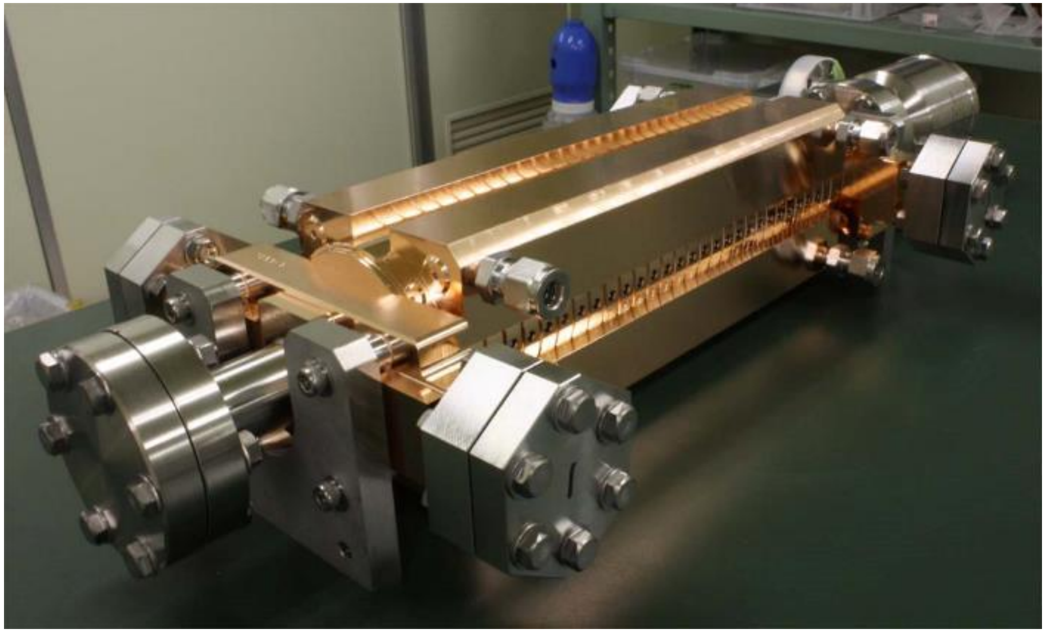
damped



4. TD24_Disk_#4

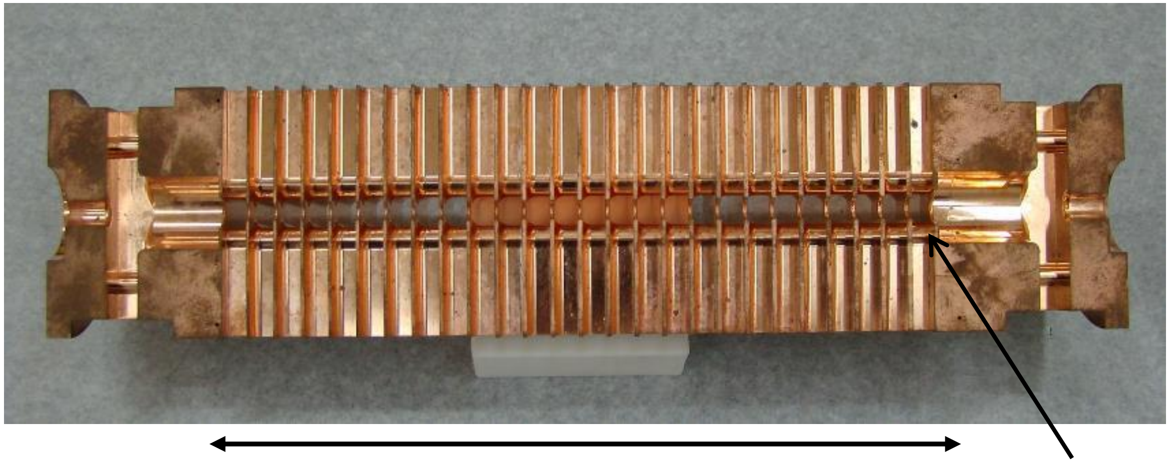
CLIC accelerating structure

Outside



11.994 GHz X-band
100 MV/m
Input power ≈50 MW
Pulse length ≈200 ns
Repetition rate 50 Hz

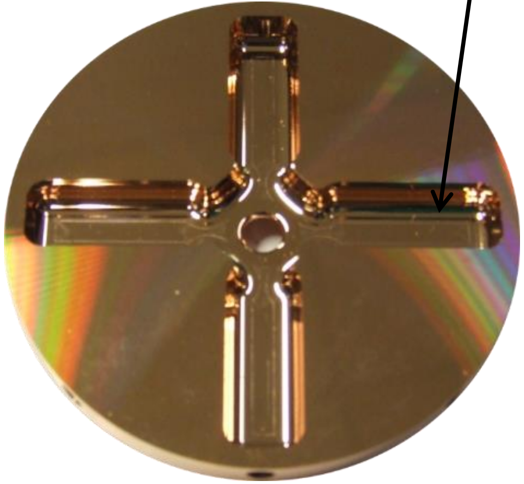
Inside



25 cm

6 mm diameter beam aperture

Micron–precision disk



HOM damping waveguide

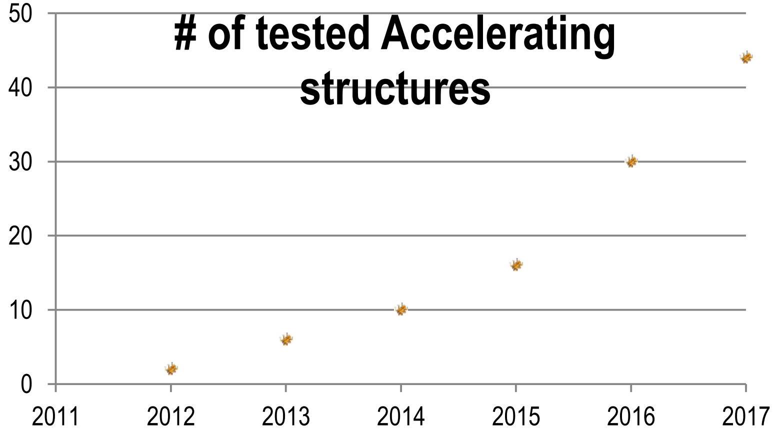
Testing structures at high power

Testing of an adequate number of structures at full power, to establish confidence in the design, is a critical part of the CLIC R&D program.

3 TeV c.m. version of CLIC would need ~ 140’000 structures **Fabrication and testing is slow.**

Tests performed or to be performed with

1. Klystrons at SLAC and KEK (but at 11,4 GHz)
2. Stand alone test stands to be built at CERN (Xbox1, Xbox2)*
3. Tests with beam on CLIC Test Facility CTF3 (Two Beam Test Stand).
4. Full beam-loading tests
5. Wake-field experiments (FACET, SLAC)



In 2006 the project changed RF frequency from 30 GHz to 12 GHz (cost optimisation found in 12 ~ 14 GHz range).

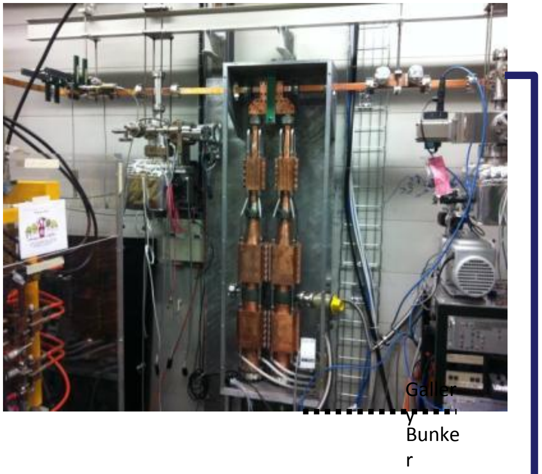
*12 GHz chosen in order to benefit from existing infra-structure from CTF3 and LEP Injector Linac (3 GHz)

Problem – no availability of high power commercial klystrons at 12 GHz.

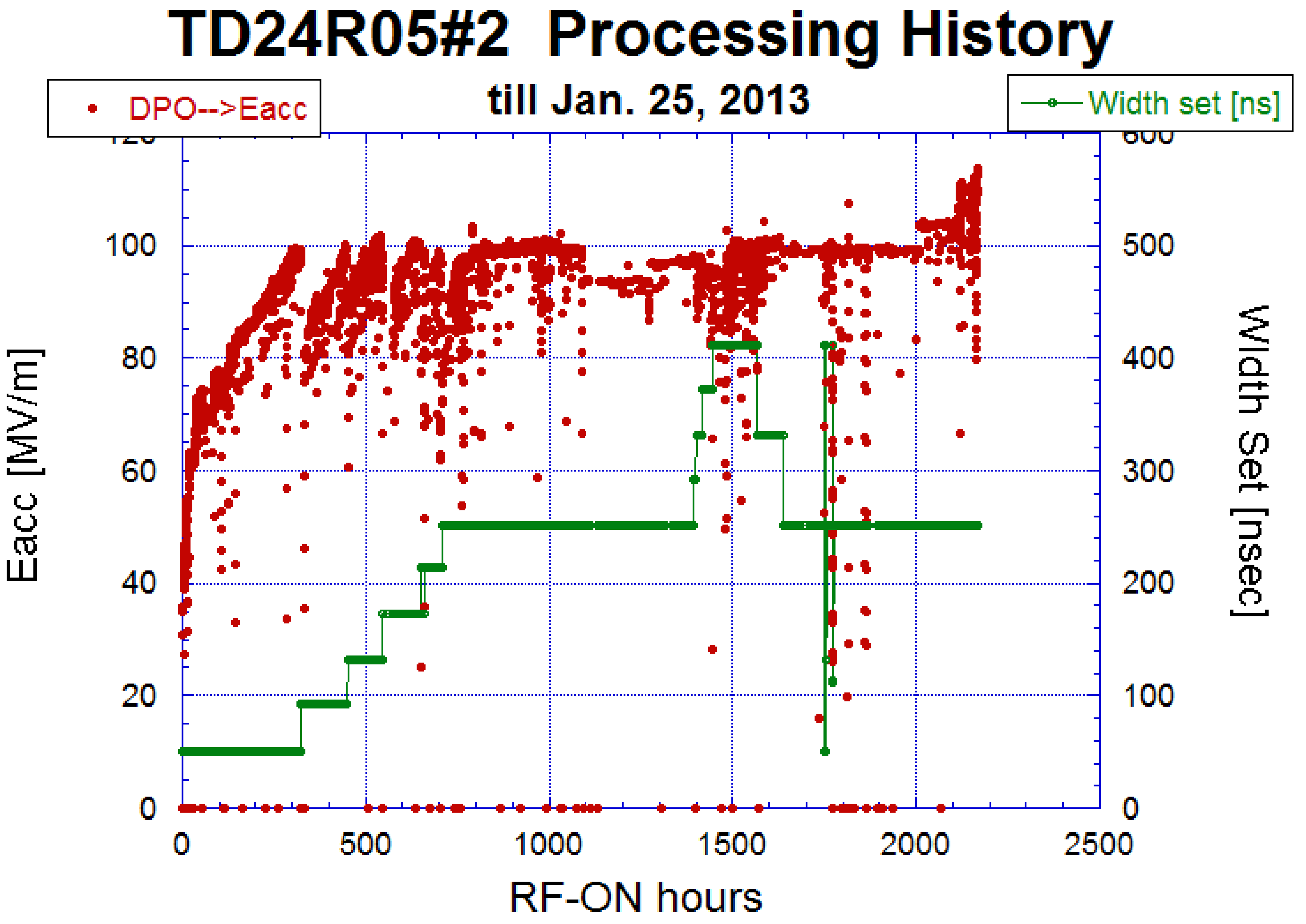
Layout of the CERN X-band test stand (X-box 1)

Clockwise from top-left:

- Modulator
- XL5 klystron (SLAC)
- RF Pulse compressor
- DUT + connections
- Accelerating structure

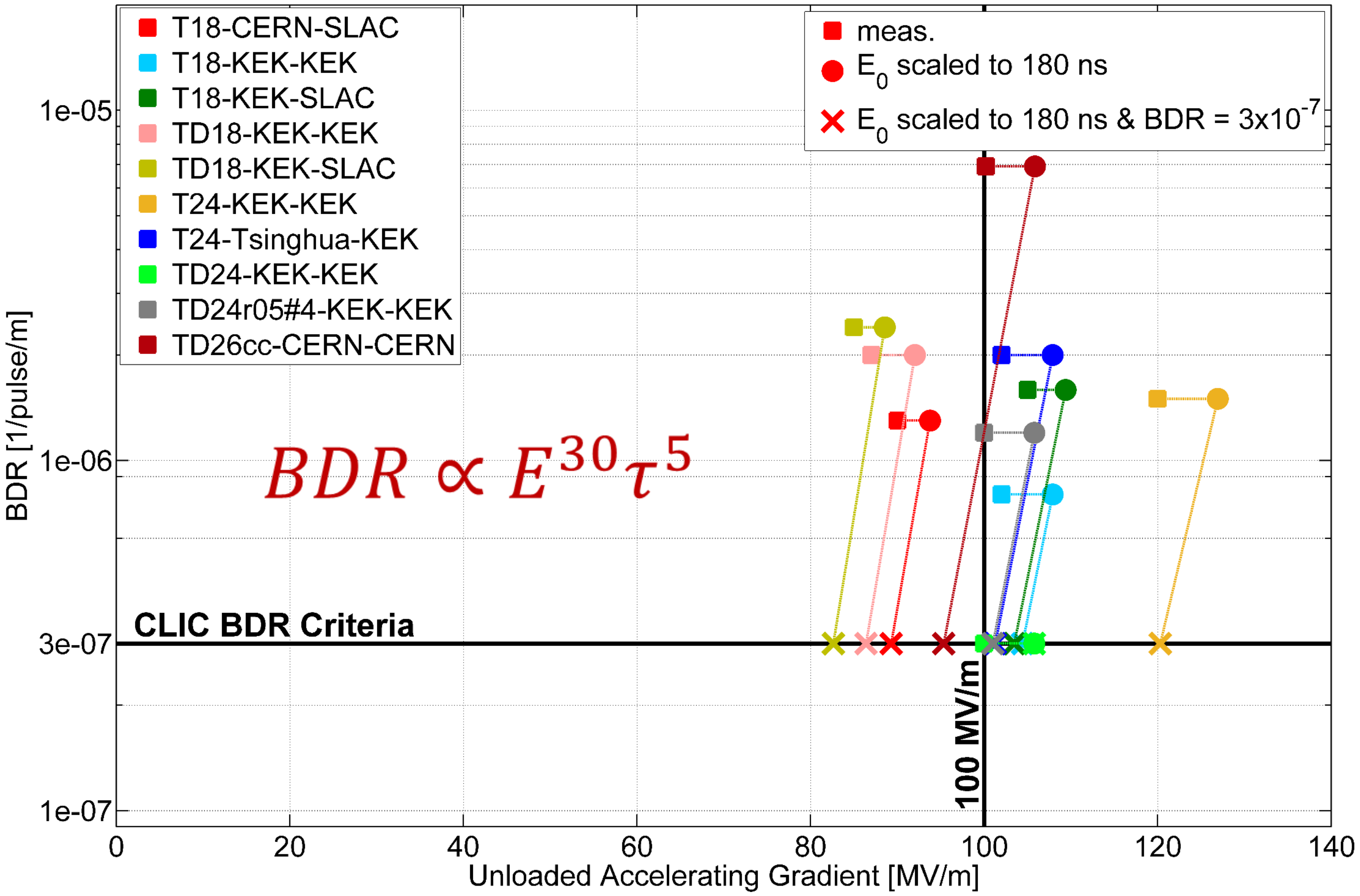


Conditioning; the process by which the structure is gradually brought to its full performance limits (c.f. SC magnet “training”)



Challenge :how to reduce the conditioning time required ? Structure preparation / treatment.

Performance summary at CLIC specifications



$$BDR \propto E^{30}\tau^{5}$$

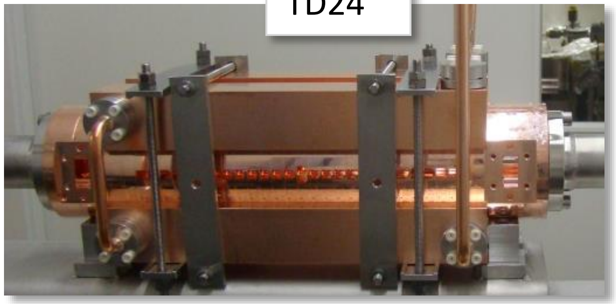
Two-Beam Acceleration (gradient and BDR achieved)

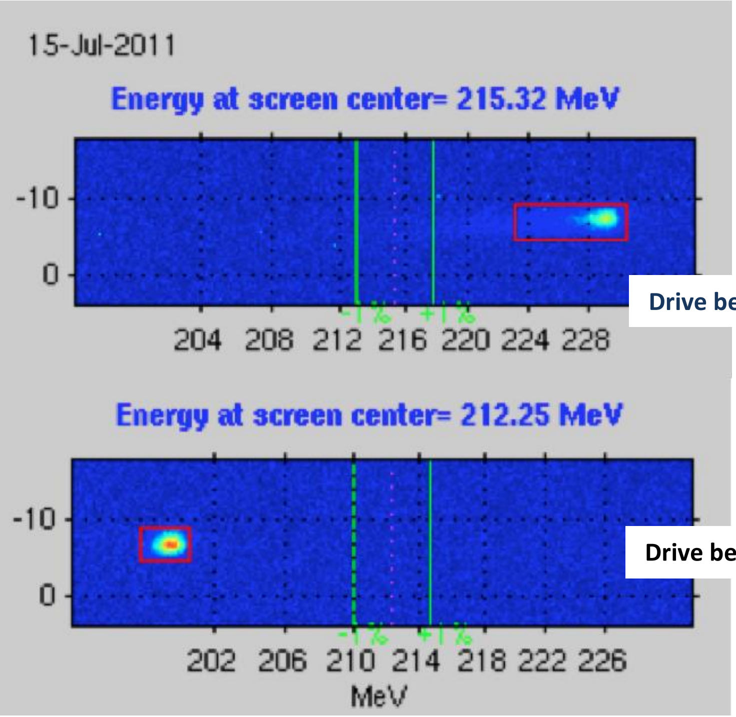
Two-Beam Acceleration demonstration in TBTS

Up to 145 MV/m measured gradient

Good agreement with expectations (power vs. gradient)

TD24



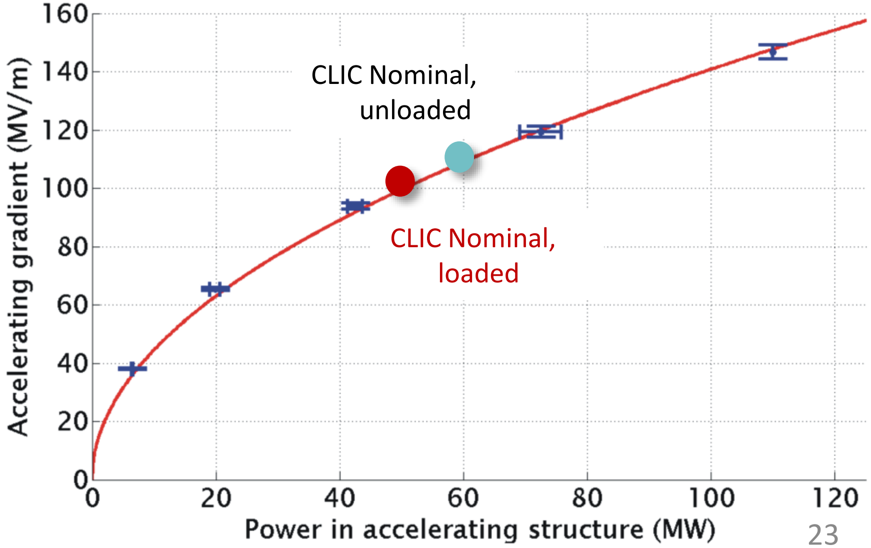


Drive beam ON

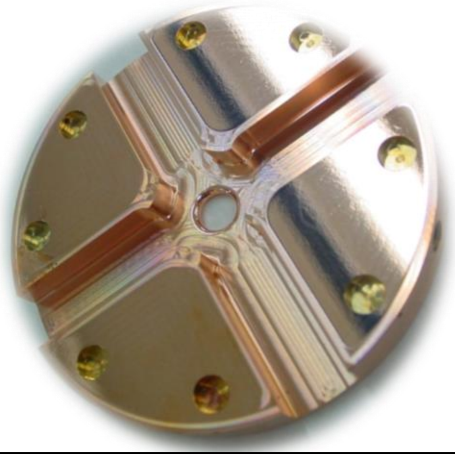
Drive beam OFF

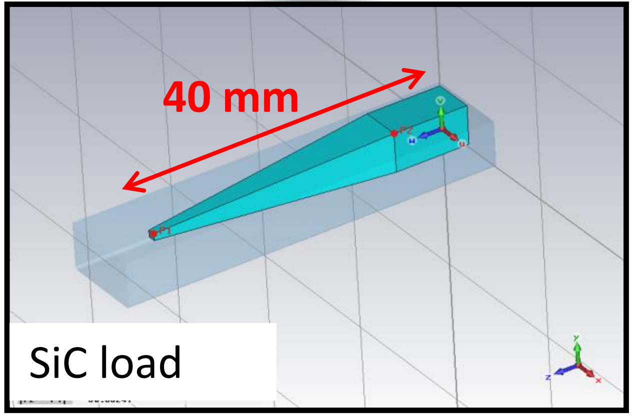
Maximum stable probe beam acceleration measured: 31 MeV

⇒ Corresponding to a gradient of **145 MV/m**

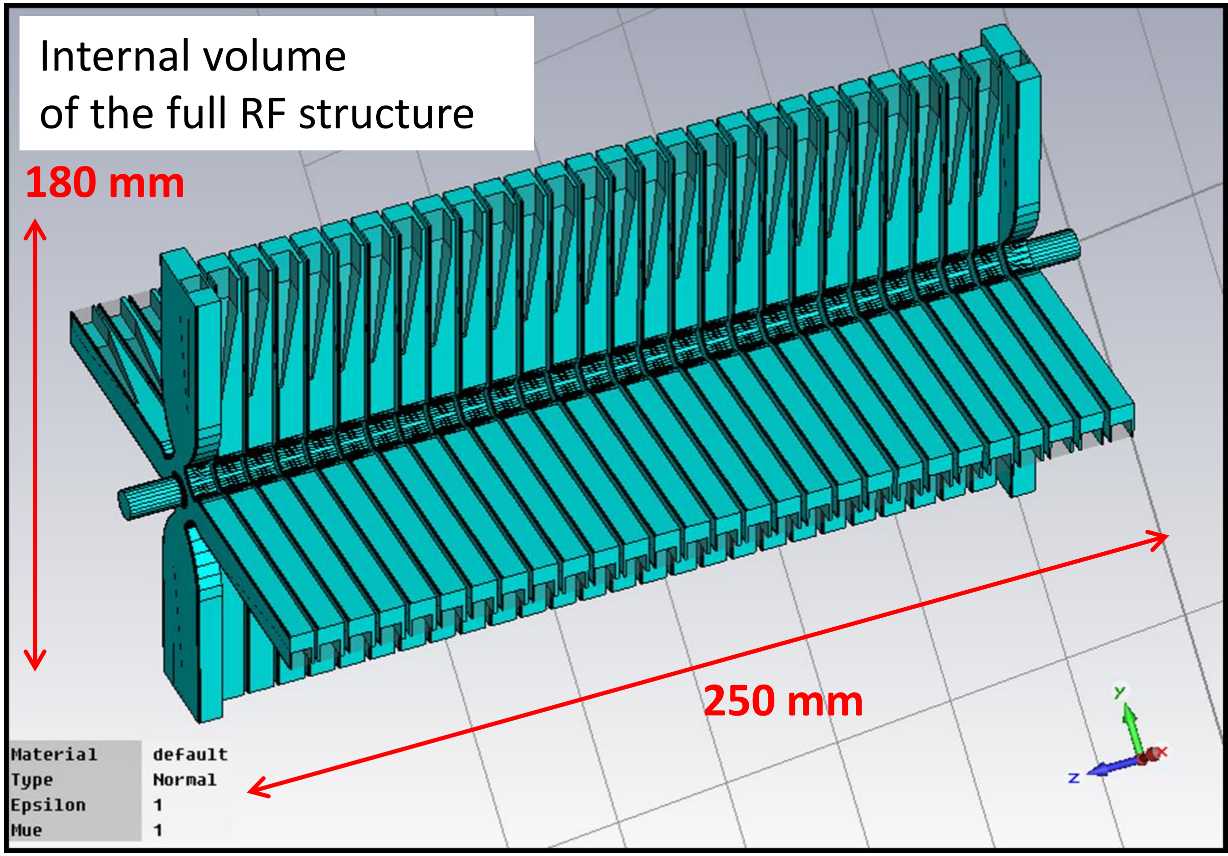


The CLIC accelerating structure – **wakefield mitigation**





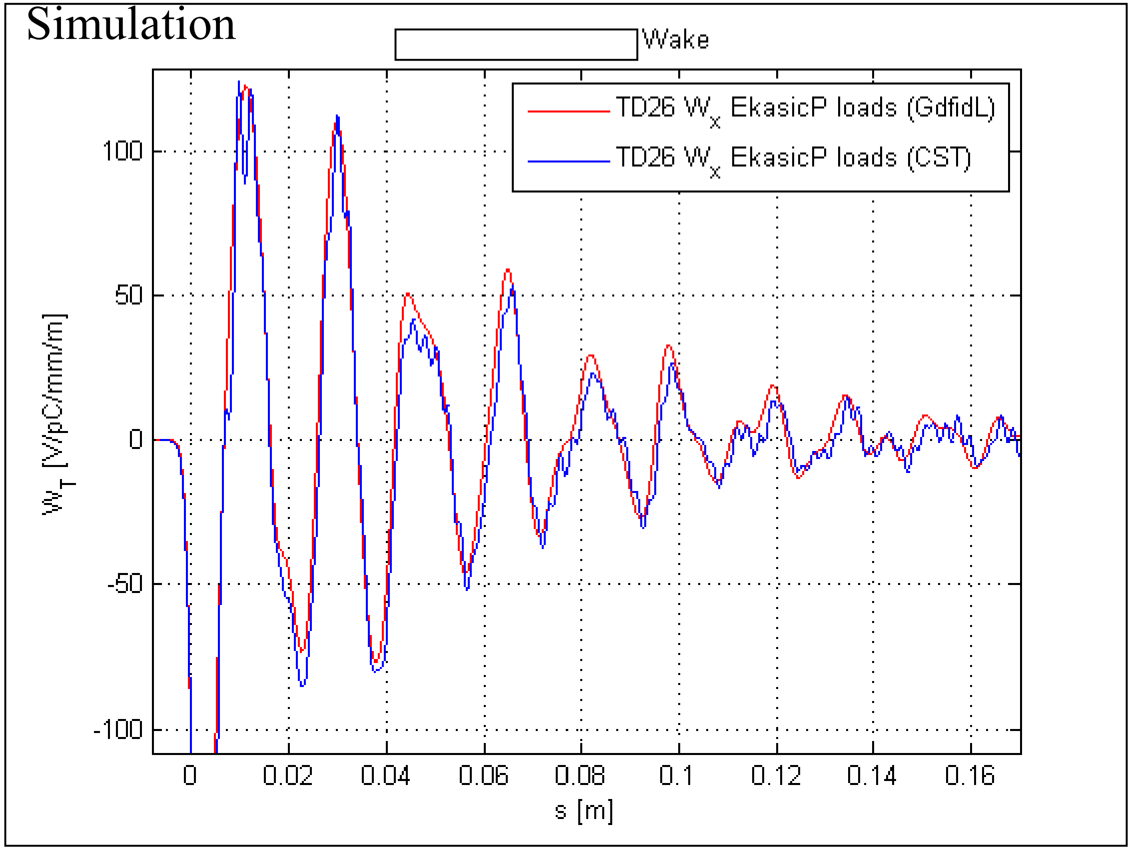
SiC load

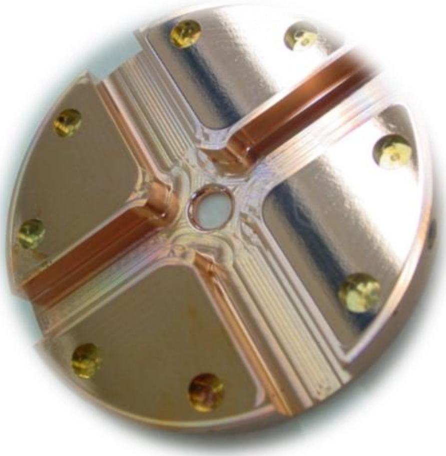

Internal volume
of the full RF structure

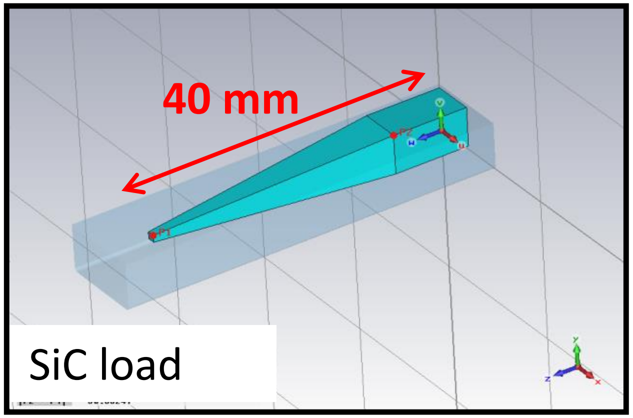
Material	default
Type	Normal
Epsilon	1
Mue	1

The dielectric properties of the load material (ε_r, tan δ) were first determined experimentally over a large range of frequencies (De Michele, Pieloni)
« EM characterization of damping materials for CLIC RF accelerating structures »,
De Michele and Grudiev, paper in preparation.

Can the wakes be sufficiently damped before the arrival of the trailing bunch?



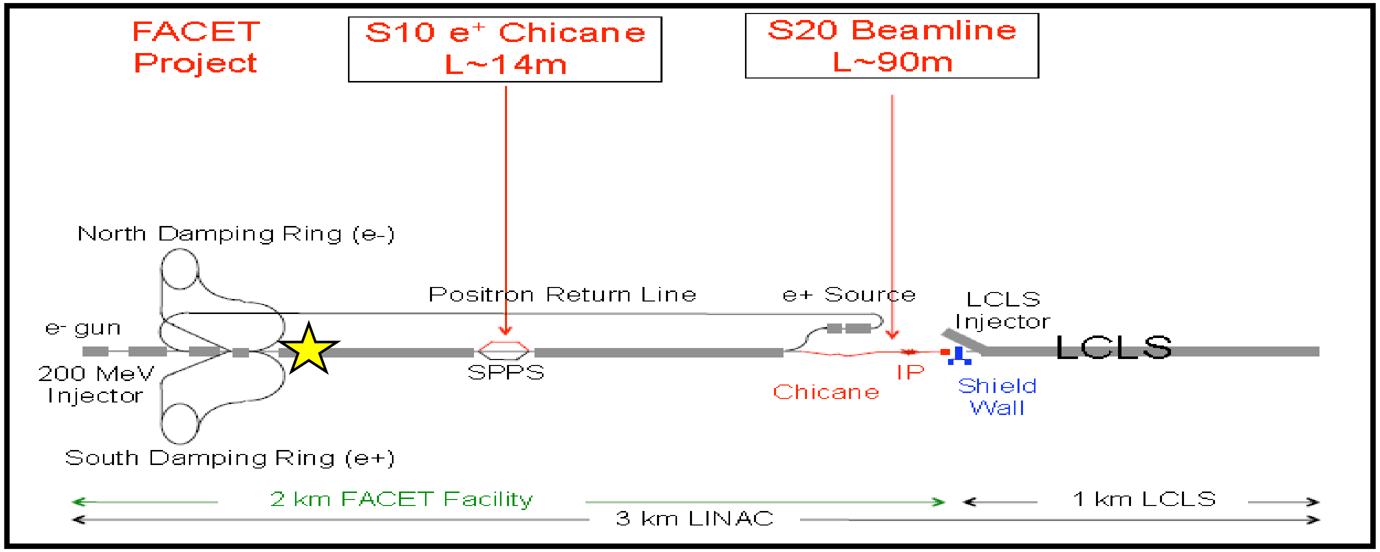




Experimental confirmation would be desirable (before building 30 km of them!)

Experiment at FACET (SLAC)

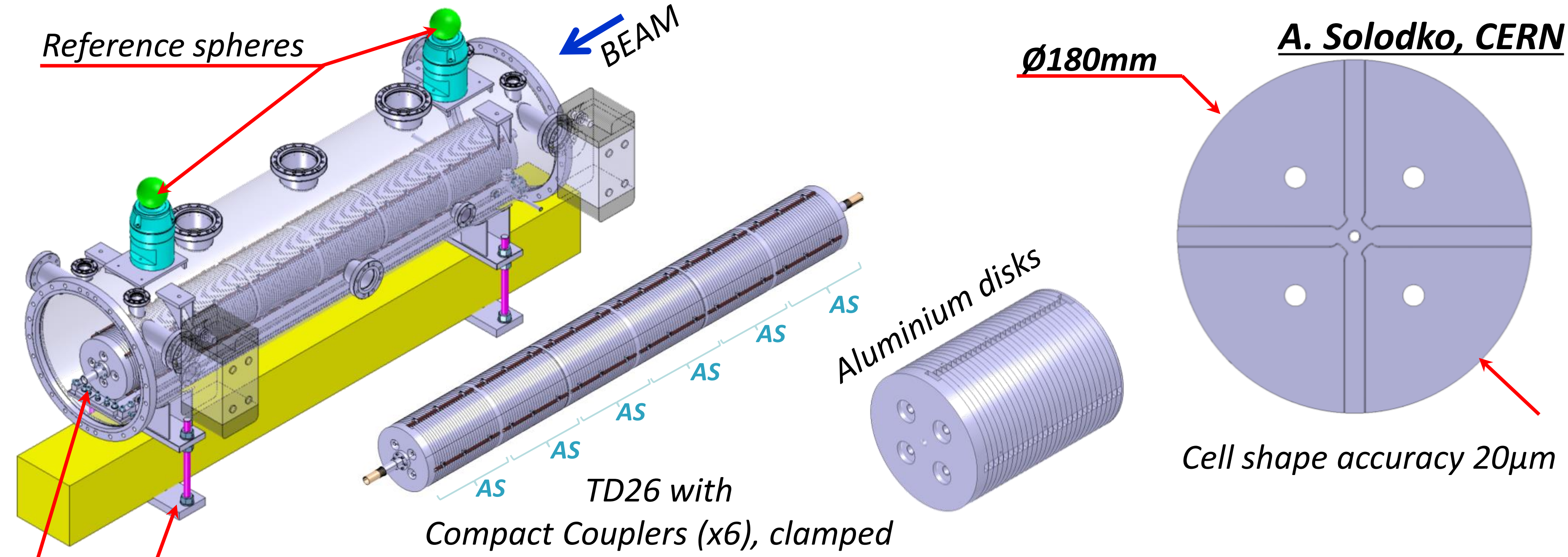
Aim: Measure the wake-fields using positron (drive) and electron (witness) bunches.
Wake-fields are excited by **driving positron bunch** passing through the structure with an offset from the linac axis.
The **electron witness bunch** gets a kick from the excited wake-fields.
The **transverse wakefield** can be calculated from the measurements of the deflecting angle of the witness bunch with respect to a reference trajectory.



$$\Delta\phi_y = \frac{q_w Q_d L e^{-\left(\frac{\omega\sigma_d}{2c}\right)^2} e^{-\left(\frac{\omega\sigma_w}{2c}\right)^2}}{E_w} \cdot W_\perp(t)\Delta y_d$$

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

CLASSE Experiment at SLAC – mapping out the wake-fields



Reference spheres

A. Solodko, CERN

Ø180mm

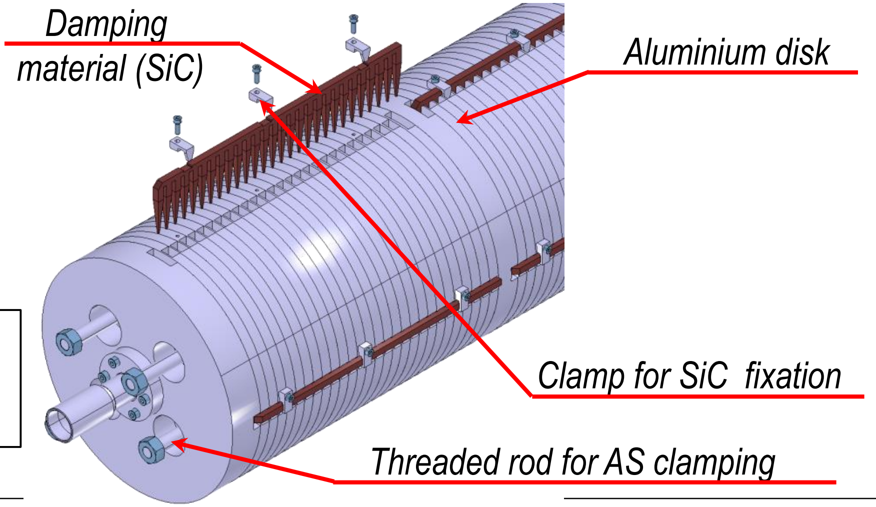
Aluminium disks

Cell shape accuracy 20µm

TD26 with
Compact Couplers (x6), clamped

Features for Tank
alignment on the girder

Features for AS
alignment in the Tank



Damping material (SiC)

Aluminium disk

Clamp for SiC fixation

Threaded rod for AS clamping

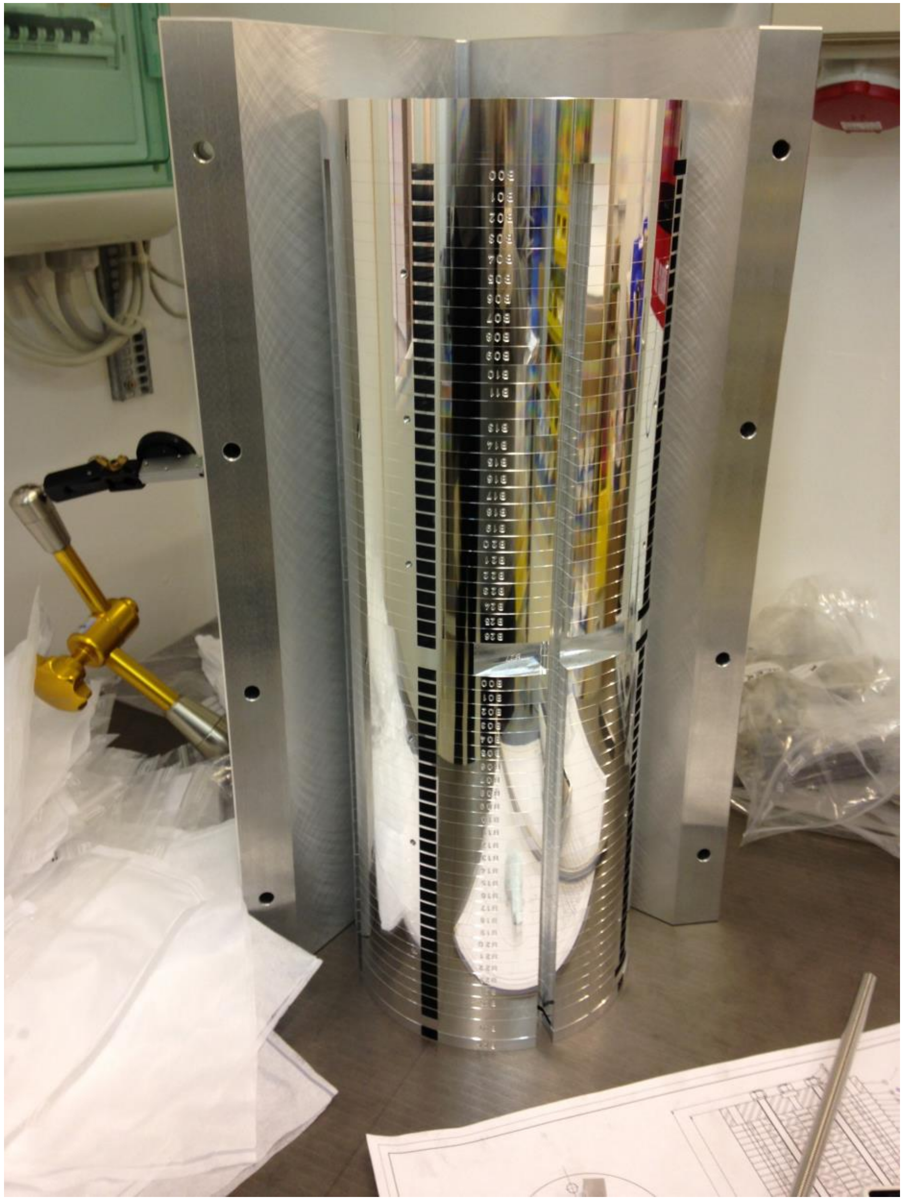
6 sections, 26 cells each, compact coupler design

Clamped aluminum disks

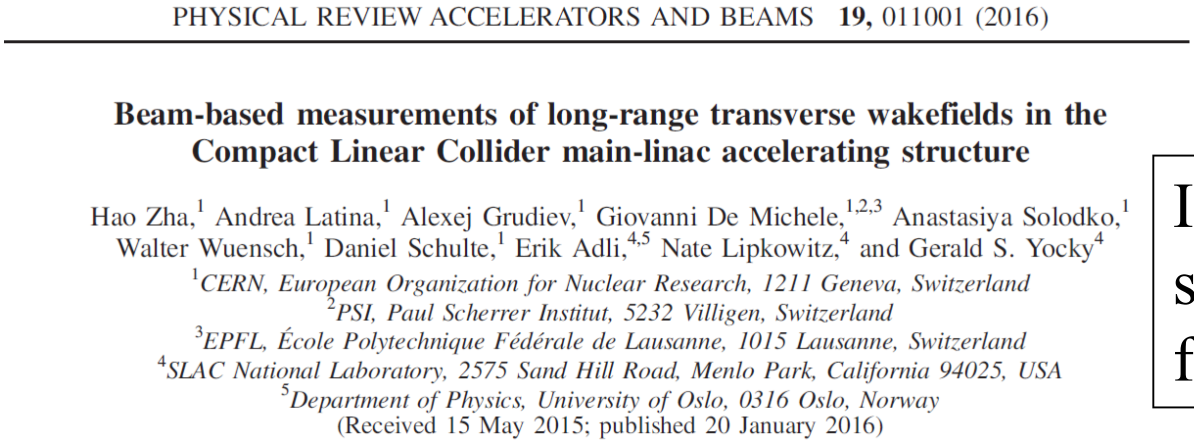
Multi-Purpose Test Structure

Fabricated from aluminium cells clamped together.

“Passive” structure i.e. no high power RF. Only the beam excited wakefield.



Wakefield measurements at FACET (SLAC)



PHYSICAL REVIEW ACCELERATORS AND BEAMS **19,** 011001 (2016)

Beam-based measurements of long-range transverse wakefields in the Compact Linear Collider main-linac accelerating structure

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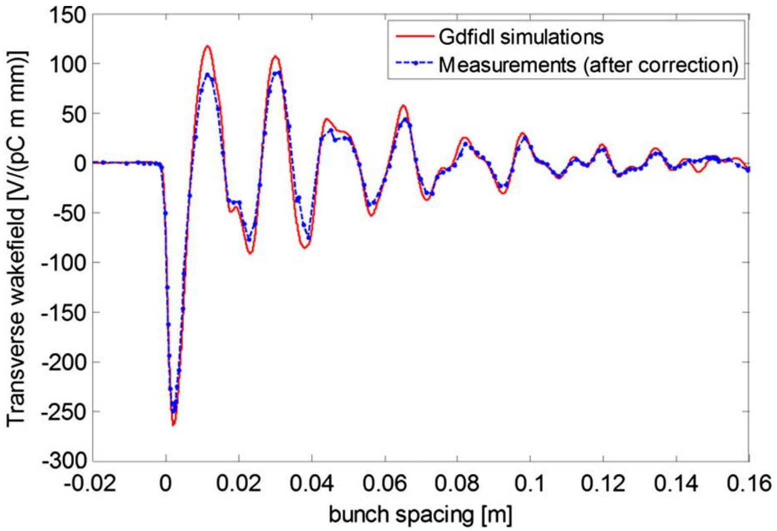
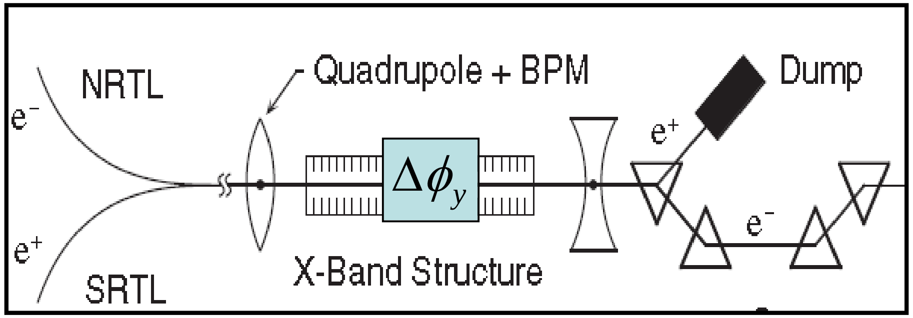
(Received 15 May 2015; published 20 January 2016)

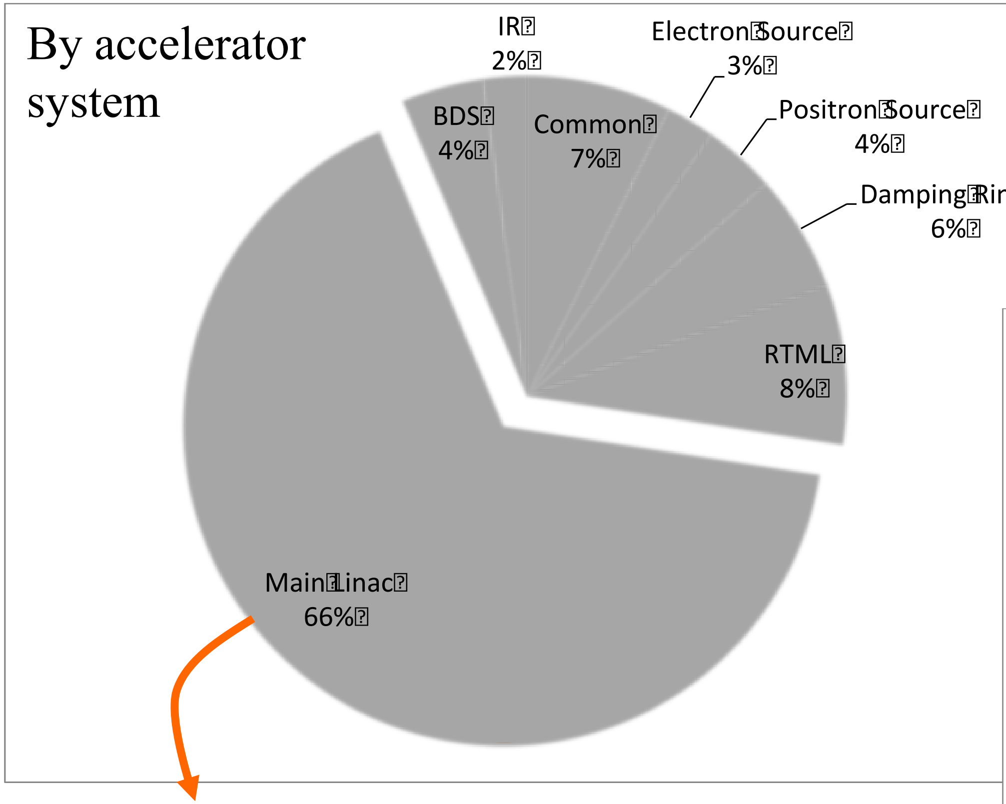
Impressive agreement with simulations. Important step forward for CLIC.



So, is this the CLIC structure ? More high power tests are planned. Included in CERN budget.

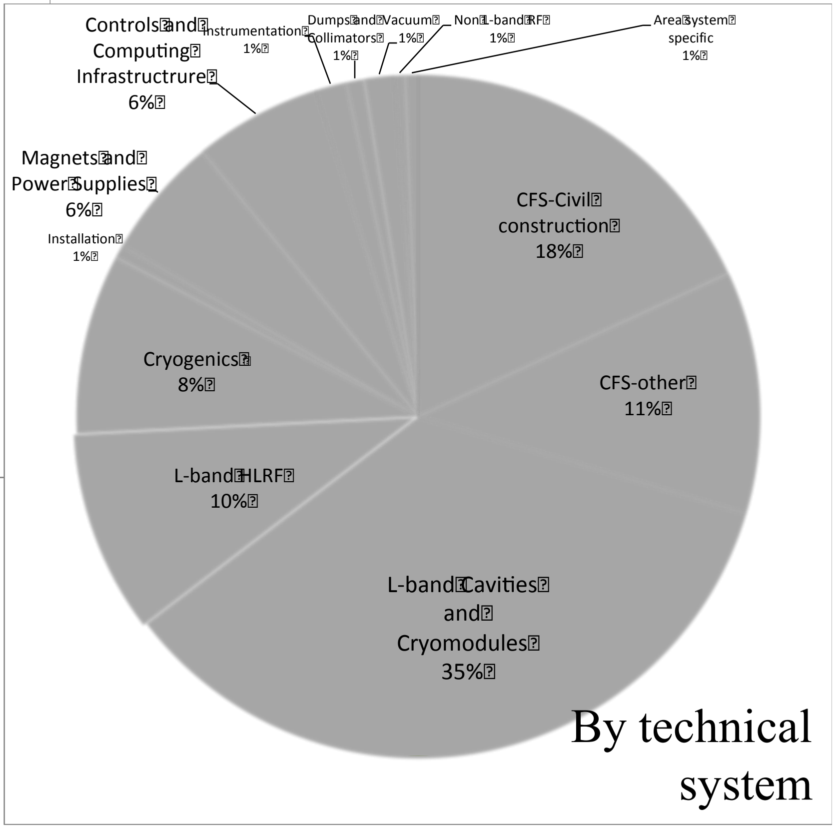


Challenges: financial - TDR Value Estimate



7.8 Billion ILCU
22.6 Million person-hours

CFS-Civil construction	10%
CFS-other	6%
L-band Cavities and Cryomodules	32%
L-band HLRF	9%
Cryogenics	7%
Controls	2%
TOTAL Main Linac	**66%**



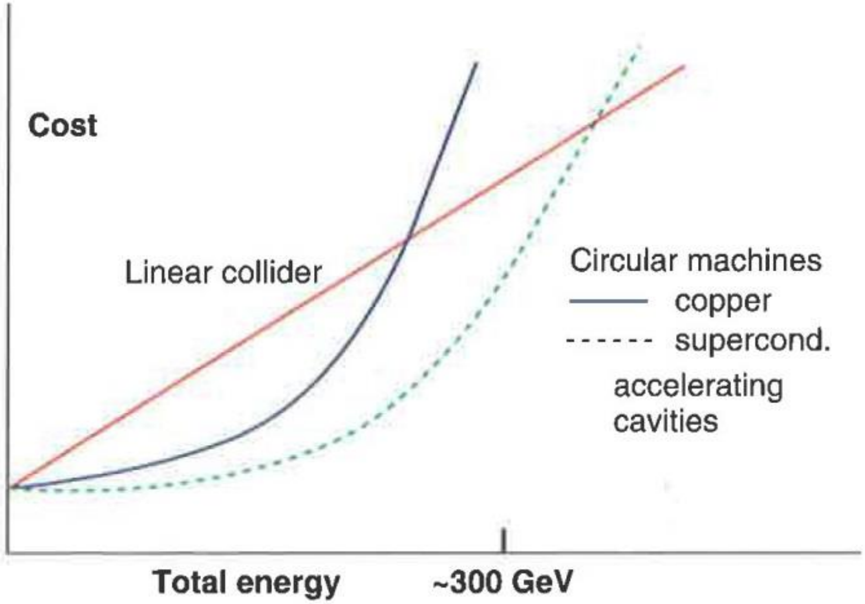
And why not another e+e- ring?

The CLIC study group set itself the objective of providing a c.o.m. energy one order of magnitude above that of LEP-II.

“An *e^+-e^-* storage ring in the range of a few hundred GeV in the centre of mass can be built with present technology. ...would seem to be ... most useful project on the horizon.” (original LEP proposal, 1976)

B. Richter, *Very High Energy Electron-Positron Colliding Beams for the Study of Weak Interactions*, NIM 136 (**1976**) 47-60

350 GeV c.m.
↔
~90 km
cost-optimized
circumference



Future Circular Collider Study

GOAL: CDR and cost review for the next ESU (2018)

International FCC collaboration (CERN as host lab) to study:

- ***pp*-collider (*FCC-hh*)**
  → main emphasis, defining infrastructure requirements

~16 T ⇒ 100 TeV *pp* in 100 km

- **80-100 km infrastructure** in Geneva area
- **e^+e^- collider (*FCC-ee*)** as potential intermediate step
- ***p-e* (FCC-he) option**
- **HE-LHC** with FCC-hh technology

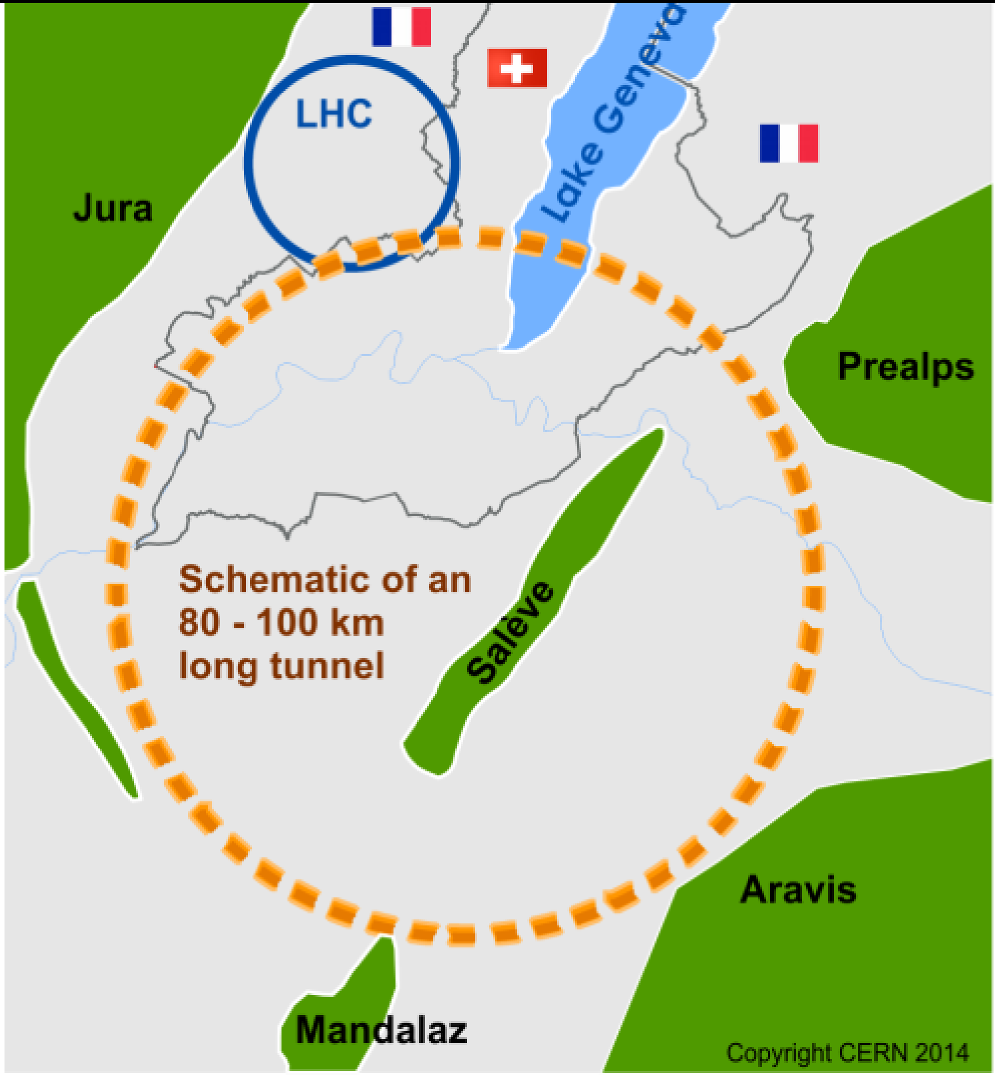


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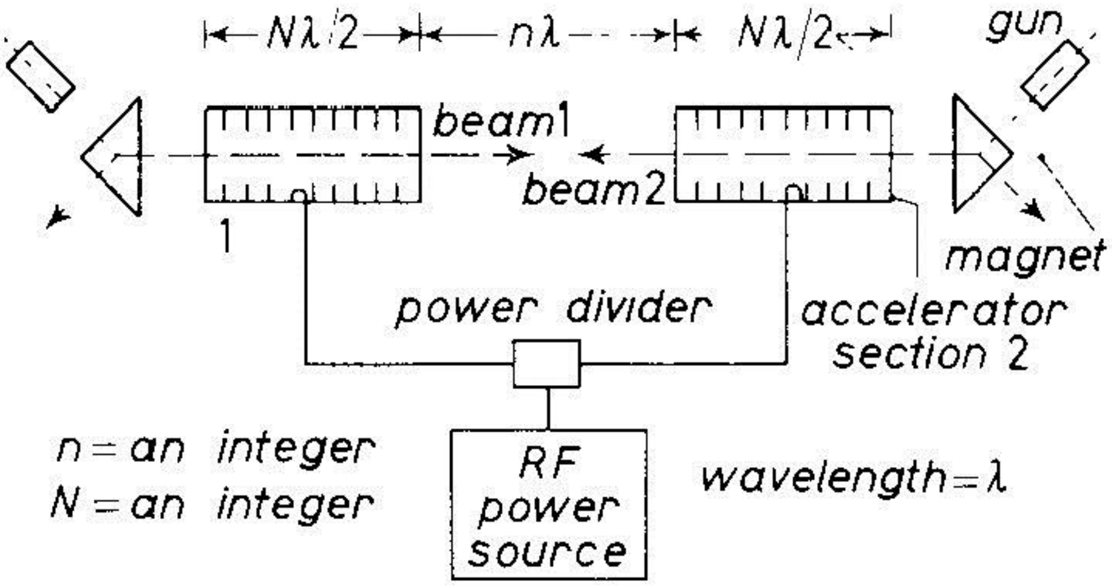
Table 1: Parameter table defined for the FCC kickoff meeting.

	LEP1	LEP2	Z	W	H	tt
Circumference [km]	26.7		100			
Bending radius [km]	3.1		11			
Beam energy [GeV]	45.4	104	45.5	80	120	175
Beam current [mA]	2.6	3.04	1450	152	30	6.6
Bunches / beam	12	4	16700	4490	1360	98
Bunch population [10^{11}]	1.8	4.2	1.8	0.7	0.46	1.4
Transverse emittances						
- Horizontal [nm]	20	22	29.2	3.3	0.94	2
- Vertical [pm]	400	250	60	7	1.9	2
Momentum comp. [10^{-5}]	18.6	14	18	2	0.5	0.5
Betatron function at IP β^*						
- Horizontal [m]	2	1.2	0.5	0.5	0.5	1
- Vertical [mm]	50	50	1	1	1	1
Beam size at IP σ^* [μm]						
- Horizontal	224	182	121	41	22	45
- Vertical	4.5	3.2	0.25	0.084	0.044	0.045
Energy spread [%]						
- Synchrotron radiation	0.07	0.16	0.04	0.07	0.10	0.14
- Total (including BS)	0.07	0.16	0.06	0.09	0.14	0.19
Bunch length [mm]						
- Synchrotron radiation	8.6	11.5	1.64	1.01	0.81	1.16
- Total	8.6	11.5	2.56	1.49	1.17	1.49
Energy loss / turn [GeV]	0.12[1]	3.34	0.03	0.33	1.67	7.55
SR power / beam [MW]	0.3[1]	11	50			
Total RF voltage [GV]	0.24	3.5	2.5	4	5.5	11
RF frequency [MHz]	352		800			
Longitudinal damping time τ_E [turns]	371	31	1320	243	72	23
Energy acceptance RF [%]	1.7	0.8	2.7	7.2	11.2	7.1
Synchrotron tune Q_s	0.065	0.083	0.65	0.21	0.096	0.10
Polarization time τ_p [min]	252	4	11200	672	89	13
Hourglass factor H	1	1	0.64	0.77	0.83	0.78
Luminosity/IP [10^{34} cm^{-2}s^{-1}]	0.002	0.012	28.0	12.0	6.0	1.8
Beam-beam parameter						
- Horizontal	0.044	0.040	0.031	0.060	0.093	0.092
- Vertical	0.044	0.060	0.030	0.059	0.093	0.092
Luminosity lifetime [min][2]	1750	434	298	73	29	21
Beamstrahlung critical	No		No	No	Yes	Yes

[1] Does not take into account the contribution of damping and emittance wigglers.

[2] The luminosity lifetime corresponds to 4 IPs.

Earliest linear-collider proposal



Maury Tigner, "*A Possible Apparatus for "Clashing"-Beam Experiments*", Nuovo Cimento 37, 1228 (**1965**)

50 years ago already !

Tigner recognised already then that, due to the high beam powers, there would be a strong advantage in using superconducting RF.
He also noted that if the beams could be recirculated in SC linacs at a decelerating phase one could recover the energy of the spent beam !

En guise de conclusion

Future high energy electron-positron colliders (linear or otherwise) present severe technical, scientific, financial and organisational challenges, not to mention, motivational.

Young engineers / physicists taking up these challenges are at least assured of lots of

Many thanks for your attention !